Analysis of Cross-Industry Interactions to Reach a Resource-Efficient and Low-Carbon Future

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Abbreviations

CE	Circular Economy
CUD	Communauté Urbaine de Dunkerque (Dunkirk Urban Community)
DAM	Day Ahead Market
DH&CN	District Heating and Cooling Network
DHN	District Heating Network
EMF	Ellen MacArthur Foundation
EPOS	Enhanced energy and resource Efficiency and Performance in process industry Operations via onsite and cross-sectorial Symbiosis
EU	European Union
GPMM	Grand Port of Marseille Mediterranean
H2020	Horizon 2020
IE	Industrial Ecology
IS	Industrial Symbiosis
IM	Imbalance Market
LESTS	Legal Economic Spatial Technical Social
MLP	Multi-Level Perspective
NISP	National Industrial Symbiosis Programme
PPP	People Planet Profit
PV	Photo Voltaic
SDGs	Sustainable Development Goals
TSO	Transmission System Operator
VPP	Virtual Power Plant

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SUMMARY

In 2017, industry accounted for the 24.6% of the total final energy consumption in EU-28 (Statistical Office of the European Communities, 2019), while the year before, their material waste amounted to 2.5 billion tonnes (Eurostat, 2016). These numbers signify the impact that industries can have on the move to a resource-efficient and low-carbon future. Optimisation of industrial sites through efficiency gains, carbon and energy savings and the use of renewable energy sources serves as a starting point in this regard. However, the system boundaries can be widened to include other industries, other process sectors and neighbouring municipalities.

For the past three decades, the field of industrial ecology has focused on cross-boundary interactions of industries and other economic agents. Industrial ecology tries to understand the workings of these interactions in a system's perspective and predict patterns that will result in a resource efficient future. The study of system transition using the multi-level perspective, although it did not emerge within the field of industrial ecology, has similarities with industrial ecology in finding emergent patterns within complex systems. Thus, the field of industrial ecology, the theories of complex systems and multi-level perspective, were tremendous help in the academic framing of this thesis. Two of the 17 UN's Sustainable Development Goals proved to be the beacon that guided all the work carried out in the four years of the research. The first one is Goal 9, which focuses on building resilient infrastructure, promoting inclusive and sustainable industrialization, and fostering innovation. This goal inspired the first part of the thesis, which focuses on industrial cooperation for energy and resource efficiency. The other one is Goal 7, which aims to ensure access to affordable, reliable, sustainable and modern energy for all. This goal motivated the second part of the thesis, which focuses on the transition to a low-carbon energy system.

The overall aim of this thesis is to explore the potential of process industries to cooperate in a sustained fashion among each other and with other public-and-private actors to move towards an energy and resource efficient future. This aim defines the research question that is confronted in this thesis:

How can cross-boundary industrial interactions help the move towards resource-efficient and low-carbon future?

The first part of this thesis deals with the improvements in resource utilisation processes in industry through industrial symbiosis. Industrial symbiosis has proven to bring collective benefits to multiple stakeholders by minimising underutilised resources, sharing knowledge and improving business and technical processes. This analysis was limited to existing and potential industrial symbioses in five different locations across Europe. Two of the locations, Dunkirk (France) and Visp (Switzerland) had an district heating network and the other three, Humber (UK), Lavéra (France), and Rudniki (Poland) were primarily focused on symbiosis between the industries.

The data collection and the content analysis was divided into five aspects Legal, Economic, Spatial, Technical, and Social (LESTS). The LESTS methodology and the LESTS survey helped to reach conclusive remarks about the dynamics of symbiosis. This helped to understand the preconditions for engaging in successful symbiosis. Furthermore, potential industrial symbioses were proposed to the industries, complemented with a numeration of their strengths, weaknesses, opportunities, and threats. The LESTS surveys

proved to be comprehensive in their design for data gathering because of the focus on technical, as well as, non-technical information. These surveys helped to identify 28 industrial symbioses in the three industrial clusters. The case study also resulted in proposing three improvements in the LESTS methodology. First, to consider the length of time it requires to fill in the LESTS surveys, hence to streamline them to a single objective and to reduce the data collection time and effort. Second, to include more local actors in the process of symbiosis identification via a workshop or brokerage event. Third, to include an objective method to compare different industrial symbioses and prioritise them based on a cost-benefit analysis.

The two examples of the district heating networks led to a good understanding of the evolution of the industrial symbiosis surrounding public-private partnership. The Visp district heating and cooling network has emerged as a result of the self-organisation by the public and private actors. Industrial symbiosis particular to the Dunkirk district heating network was first facilitated by the public authorities and then evolved to engage in more strategic and goal-oriented processes. The Dunkirk cluster (wider than the heating network) provides lessons for future cities that are in harmony with industrial evolution and vice versa. The rest of the industrial clusters proved to possess untapped potential to engage in future industrial symbiosis.

The second part of the thesis deals with the shift in the existing energy system to a low-carbon system. The second case study includes an agent-based model of a virtual standalone electricity network to identify how the demand side response from industries can support the transition to a grid fed by 100% renewable energy. 5500 simulations results in data generation that helped to quantify the effect of feed-in tariffs for wind farm owners, the increasing generation capacity of wind energy, and demand side response from industries on the consumption of energy from renewable sources and imbalance market prices.

The second case study concluded that if the industries provide demand side response they can contribute significantly in keeping the grid in balance in the case of fluctuation in supply, which is typical of renewably sourced energy. The agent-based model showed that the industrial flexibility to a maximum of 25% provides the most profit to the flexible industries without compromising the loss of profits due to hindered production processes. As an extra result, it was found that the producers of wind energy without storage facilities face no effect on their profits under changing industrial demand flexibility. However, the producers with storage, who already have higher costs of production, face a further deterioration of profits when the industrial flexibility increases from 0% to 25%. This shows a need for future market mechanisms for wind energy producers that will incentivise them to invest in supply management (storage) when industries are providing demand side response for grid balancing.

SAMENVATTING

In 2017 was de industrie goed voor 24,6% van het totale eindverbruik van energie in de 28 landen van de Europese Unie (Bureau voor de Statistiek van de Europese Gemeenschappen, 2019), terwijl het jaar ervoor hun materiaalafval 2,5 miljard ton bedroeg (Eurostat, 2016). Deze cijfers duiden op de impact die industrieën kunnen hebben op de overgang naar een hulpbronnenefficiënte en koolstofarme toekomst. De optimalisatie van industriële locaties door efficiëntere productiemethodes, koolstof- en energiebesparingen en het gebruik van hernieuwbare energiebronnen dient in dit verband als uitgangspunt. De systeemgrenzen kunnen echter worden uitgebreid met andere industrieën, andere sectoren van de verwerkende industrie en aangrenzende gemeenten.

De afgelopen drie decennia hebben onderzoekers op het gebied van industriële ecologie zich gericht op grensoverschrijdende interacties van industrieën en andere economische actoren. Industriële ecologie probeert de werking van deze interacties in het perspectief van een systeem te begrijpen en patronen te voorspellen die zullen resulteren in een hulpbronnenefficiënte toekomst. De studie van systeemtransitie die gebruikt van een multi-level perspectief – hoewel niet voortgekomen uit het wetenschappelijke terrein van industriële ecologie – deelt overeenkomsten met dit terrein waar het aankomt op het vinden van opkomende patronen binnen een complex systeem. Het wetenschappelijke terrein van industriële ecologie, de theorieën van complexe systemen en het multi-level perspectief waren dus een enorme hulp bij het academisch plaatsen van dit proefschrift. Twee van de 17 duurzame ontwikkelingsdoelen van de Verenigde Naties bleken het baken te zijn dat al het werk leidde dat in de vier jaar van het onderzoek werd uitgevoerd.

Het eerste doel is doel negen. Dit doel richt zich op het bouwen van veerkrachtige infrastructuur, het bevorderen van inclusieve en duurzame industrialisatie en het bevorderen van innovatie. Doel negen inspireerde het eerste deel van het proefschrift, dat zich focust op industriële samenwerking om energie- en hulpbronnenefficiëntie te verbeteren. Het andere doel is doel zeven. Dit doel beoogt de toegang tot betaalbare, betrouwbare, duurzame en moderne energie voor iedereen te waarborgen. Doel zeven motiveerde het tweede deel van het proefschrift, dat zich richt op de overgang naar een koolstofarm energiesysteem.

Het algemene doel van dit proefschrift is het verkennen van het potentieel van verwerkende industrieën om op een duurzame manier onderling en met andere publieke en private actoren samen te werken om zo een energie- en hulpbronnenefficiënte toekomst te bereiken. Dit doel bepaalt de hoofdvraag van dit proefschrift:

Hoe kunnen grensoverschrijdende industriële interacties de overgang naar een hulpbronnenefficiente en koolstofarme toekomst helpen?

Het eerste deel van dit proefschrift behandelt de verbeteringen in processen voor het gebruik van hulpbronnen in de industrie door industriële symbiose. Het is bewezen dat industriële symbiose collectieve voordelen oplevert voor meerdere belanghebbenden door onderbenutte middelen te minimaliseren, kennis te delen en zakelijke en technische processen te verbeteren. Deze analyse beperkte zich tot de evaluatie van bestaande en potentiële industriële symbioses op vijf verschillende locaties verspreid over Europa. Twee van deze locaties – te weten Duinkerken in Frankrijk en Visp in Zwitserland – hadden een industrieel verwarmingsnetwerk. De andere drie – te weten Humber in Groot-Brittannië, Lavéra in Frankrijk en Rudniki in Polen – waren voornamelijk gericht op symbiose tussen de industrieën.

De twee voorbeelden van stadsverwarmingsnetwerken hebben geleid tot een goed begrip van de evolutie van de industriële symbiose rond publiek-private samenwerking. Het stadsverwarmings- en koelingsnetwerk van Visp is ontstaan als gevolg van de zelforganisatie door publieke en private actoren. De industriële symbiose die eigen is aan het stadsverwarmingsnetwerk van Duinkerken, werd eerst door de overheid gefaciliteerd. Vervolgens ontwikkelde dit netwerk zich op zo'n manier dat het meer strategische en doelgerichte processen aanging. De cluster Duinkerken (welke breder is dan alleen het verwarmingsnetwerk) biedt lessen voor de steden van de toekomst die in harmonie zijn met industriële evolutie en vice versa. De andere drie industriële clusters bleken onaangesproken potentieel te bezitten om toekomstige industriële symbiose aan te gaan.

Het verzamelen van de gegevens en de inhoudsanalyse waren verdeeld in vijf aspecten: Juridisch, Economisch, Ruimtelijk, Technisch en Sociaal (in het Engels afgekort als LESTS). De LESTS-methodologie en de LESTS enquête hielpen bij het bereiken van concluderende opmerkingen over de dynamiek van symbiose. Dit hielp om de voorwaarden te begrijpen voor het aangaan van succesvolle symbiose. Daarenboven werden potentiële industriële symbioses voorgesteld aan de industrieën, aangevuld met een opsomming van hun sterke en zwakke punten, kansen en bedreigingen. Vanwege hun focus op zowel technische als niet-technische informatie, bleken de LESTS enquêtes in hun ontwerp allesomvattend te zijn. Deze enquêtes hielpen om 28 industriële symbioses in de drie industriële clusters te identificeren. De casestudy resulteerde ook in het voorstellen van drie verbeteringen in de LESTS-methodiek. Ten eerste, om rekening te houden met de duur van het invullen van de LESTS-enquêtes. De enquêtes moeten daarom worden gestroomlijnd tot een enkel doel en de tijd en de moeite voor het verzamelen van gegevens moeten worden verminderd. Ten tweede, om meer lokale actoren te betrekken bij het proces van symbiose-identificatie via een workshop of *brokerage-evenement*. Ten derde, om een objectieve methode op te nemen waarmee verschillende industriële symbioses kunnen worden vergelijken en geprioriteerd op basis van een kosten-batenanalyse.

Het tweede deel van het proefschrift gaat over de verschuiving van het bestaande energiesysteem naar een koolstofarm systeem. De tweede casestudy omvat een *Agent Based Model* van een virtueel zelfstandig elektriciteitsnetwerk om te bepalen hoe de vraagrespons van industrieën de overgang naar een elektriciteitsnetwerk dat wordt gevoed door 100% hernieuwbare energie kan ondersteunen. 5500 simulaties leidden tot data die bijdroegen aan het kwantificeren van het effect van feed-in-tarieven voor windenergieproducenten, van de toenemende productiecapaciteit van windenergie, en van de vraagrespons van industrieën op het verbruik van energie uit hernieuwbare bronnen en prijzen op de onbalansmarkt.

De tweede casestudy concludeerde dat als de industrieën vraagrespons bieden, ze aanzienlijk kunnen bijdragen om het net in evenwicht te houden in geval van fluctuatie in het aanbod, wat typerend is voor energie uit hernieuwbare bronnen. Het *Agent Based Model* toonde aan dat de industriële flexibiliteit tot een maximum van 25% de meeste winst oplevert voor de flexibele industrieën zonder verlies van winst als gevolg van gehinderde productieprocessen. Als extra resultaat werd vastgesteld dat de producenten van windenergie zonder opslagfaciliteiten geen effect zien op hun winst als de vraagrespons toeneemt. De producenten met opslagfaciliteiten, die al hogere productiekosten hebben, worden echter geconfronteerd met een verdere verslechtering van de winst wanneer de vraagrespons toeneemt van 0% tot 25%. Dit toont aan dat er behoefte is aan toekomstige marktmechanismen voor windenergieproducenten die hen zullen stimuleren om te investeren in aanbodbeheer (opslag) wanneer industrieën vraagrespons bieden om het energienet te balanceren.

CHAPTER 1. INTRODUCTION

This thesis is a culmination of work carried out during four years at the energy and cluster management group of Ghent University. The research includes two case studies. The first case study on industrial symbioses was carried out as part of the H2020 Research and Innovation (R&I) project EPOS (*Enhanced energy and resource Efficiency and Performance in process industry Operations via onsite and cross-sectorial Symbiosis*). While the case study of the transition to a low-carbon grid aided by industrial flexibility is carried out by envisioning a hypothetical grid that is modelled by using agent-based modelling technique. The research aims coincide with two of the United Nations Sustainable Development Goals that were set in the 2015 Rio+20 conference. Goal 9, which focuses on building resilient infrastructure, promoting inclusive and sustainable industrialization, and fostering innovation and Goal 7, which aims to ensure access to affordable, reliable, sustainable and modern energy for all. The SDGs have emerged because of a long global pursuit to conserve environment while improving the quality of human life. Though the global focus on fighting climate change and ensuing public and private initiatives provide the context for this thesis but first, it is pivotal to start by explaining the founding concepts and theories behind the research presented.

1.1 SUSTAINABLE DEVELOPMENT AND OTHER CONCEPTS

It was back in 1972, that sustaining of a good quality of life for humans without causing unprecedented harm to the environment was made clear in the book; *The limits to growth,* published by the Club of Rome (Meadows et al., 1972). Later in 1974, the word sustainability was first used in its modern sense in the first conference of the World Council of Churches in relation to a just and sustainable society (as cited by (Dresner, 2002)). In 1987, the report from the World Commission on Environment and Development, included the aspect of social justice to the debate of sustainability and proposed the most widely quoted definition of sustainable development; *Development that meets the needs of the present generations without compromising the ability of the future generations to meet their needs* (Brundtland, 1987). This UN's report entitled *Our Common Future* will later be commonly known as the Brundtland report.

As sustainable development arose at the regional and local levels, industries also took on their role to contribute to the sustainable development goals in the local applications of Agenda 21 (United Nations, 1992). The idea of Cleaner Production developed during the preparation of the 1992 Rio Summit (United Nations, 1992, p. 21). Later in 1994 when the first European Roundtable on Cleaner Production Programmes took place, it was defined as, *Cleaner Production is the conceptual and procedural approach to production that demands that all phases of the life cycle of a product or of a process should be addressed with the objective of prevention or the minimization of short and long-term risks to humans and the environment. A total societal commitment is required for affecting this comprehensive approach achieving the goal of a sustainable society* (European Commission, 1994)

Over the years, the definitions and concepts of Cleaner Production have evolved and interlaced with the emerging theories and practices in the field of sustainable development. What started as a concept, with focus on reducing the impact on the environment and society during the production phase of the industrial process, was further expanded to activities, projects, consumption patterns, and the systems that contain all these activities. With theories and concepts, assessment methods also evolved to help, primarily with, the regulatory compliance of stricter environmental regulations. In 1970s, the Environmental Impact Assessment emerged as the instrument to help the proponents and the authorities in assessing and mitigating the environment impacts of new projects (Nath et al., 1995). With the increasing sense of complexity and inter-dependability of socio-economic and environmental impacts, the assessment method was broadened to plans and policies, specifically focusing on plans by public authorities. The new assessment method termed Strategic Environmental Assessment was adopted by the European Commission in 2001 in the Directive 2001/42/EC and was to be implemented by all member states by 2004 (Implementation of Directive 2001/42 on the Assessment of the Effects of Certain Plans and Programmes on the Environment, 2001).

The definition of sustainable development presented by Gro Harlem Brundtland, then Prime Minister of Norway, was based on three principles - economic viability, protection of the environment and social and ethical acceptance. The same principles, termed as the *triple bottom approach*, will be taken up to predict the future of successful businesses in the capitalistic world of the 21st century, in the book *Cannibals with forks* written by J.S.H Elkington in 1998 (Elkington, 1998). Elkington was right in foreseeing the increasing responsibility of business towards the environment and society. Today businesses take a more proactive approach towards socio-environmental responsibilities by going beyond the legal requirements of their respective governments. Since 1990s, businesses have included wider considerations of environmental and human rights into their business strategy and term it as Corporate Social Responsibility (CSR); or more recently, simply Corporate Responsibility (Hens et al., 2018). CSR is not an obligatory legal requirement and no one definition covers the reasons why businesses adopt CSR. It also encompasses different meanings and practices for different businesses. CSR provides an opportunity for businesses distinguish themselves from their competitors based on their socio-environmental performance; hence proving Elkington's prediction true.

By late 1990s, the idea of sustainable development had already been translated into policies, regulations, and assessment techniques. The scope of assessment was broadened from projects to even plans and policies; likewise, socio-environmental concerns made their way into the management systems. The concept of cleaner production was also widened to design, procurement, end-of-use and end-of-life stages of products. Hence, new assessment methods and tools emerged to bring a holistic overview of impacts on the environment and human health during the different stages of lifecycle of a product.

Along with the business and political interest in reducing human impact on the environment, public awareness campaigns have also added to the momentum of ideas grounded in sustainable development. In 2006, the Global Footprint Network started the Earth Overshoot Day campaign. The motive behind the campaign resides in the time required by earth systems to recover the natural resources that have extracted to fulfil human needs. The Earth Overshoot Day is defined as,

Earth overshoot day marks the date when humanity's demand for ecological resources (fish and forests, for instance) and services in a given year exceeds what Earth can regenerate in that year (Simms, 2006).

Ever since 1970, the Earth Overshoot Day has been shifting earlier than the previous year, indicating that human demands of the earth's resources far exceed the natural rate at which they are restored. Putting this concept into more academic and quantifiable terms, Rockstrom and colleagues (2009) published their seminal paper on the biophysical thresholds or boundaries set in the theories and scientific fields explaining the natural earth systems, earth's natural carrying capacity, complex systems, and resilience (Rockström et al., 2009). The work by Rockstrom et al. provided quantitative measures of where have the human activities lead the earth systems in relation to the seven of the nine planetary boundaries; climate change, ocean acidification, stratospheric ozone, global Phosphorus and Carbon cycles, atmospheric aerosol loading (not quantified), freshwater use, land use change, biodiversity loss, and chemical pollution (not quantified). Already in 2009, three of the nine thresholds (climate change, the rate of interference with nitrogen cycle, and the rate of biodiversity loss) had been crossed (Rockström et al., 2009).

With the acknowledgment of the finiteness of earth's resources and the unprecedented effect of human activity on earth's ability to restore these resources, two categories of the scientific and political reactions came about. First, reduction of extraction of primary resources by improving the efficiency of production and consumption cycles, in combination with avoidance of harmful impacts on the environment and improving the societal benefit; and second, rethinking of economic concepts that underlie the current socio-economic system.

The first category encompasses incremental changes via policy and technology, such as the invigorated commitment of Europe to resource efficiency in 2011 by devising the Roadmap to a Resource Efficient Europe (*Roadmap to Resource Efficient Europe*, 2011); reducing the carbon emissions through the Low Carbon roadmap, which suggests that a tighter cap and target would put the EU on a more cost effective pathway to 2050 (Enerdata, 2014); and development of economically viable carbon capture and storage technologies (Carbon Capture and Storage Directive, 2009). The second category includes radical (system-level) changes; such as shifting to a completely renewable energy system (Mathiesen et al., 2011), overhauling the current linear (take-make-throw away) economy (Raworth, 2017; *Towards the Circular Economy (Vol 1)*, 2013), and even suggesting economic degrowth in some parts of the world (Kallis et al., 2012).

One theory that aims at sustainable development and resource efficiency, which has gained traction in the recent decades, is of Circular Economy (CE). CE aims to mimic nature by eliminating wastes and closing material loops (*Towards the Circular Economy (Vol 1)*, 2013; UNEP, 2011). The concept of mimicking nature has been around since 1970s and can be traced back to the field of Industrial Ecology (IE) (S. Erkman, 1997; Suren Erkman, 2001; Frosch & Gallopoulos, 1989), eco-industrial park development (Lowe & Evans, 1995) and, cradle-to-cradle design (McDonough & Braungart, 2002). The field of IE is of particular relevance to this thesis and hence requires more attention.

1.1.1 Industrial Ecology and Circular Economy

The paper written by Frosch and Gallopoulos in 1989, titled *Strategies for Manufacturing* in the scientific weekly *Scientific American* led to wide acknowledgement of IE (Frosch & Gallopoulos, 1989). Although the concept of industrial ecosystems had been around since the 1970s, it was perhaps the prestige of Scientific Weekly or the fact that both authors worked for General Motors, the paper received a strong positive response (Suren Erkman, 2001). After three decades, IE has been established as an academic field with its own set of theories, and assessment methods and techniques. The first definition of IE by Graedel (1994) was inspired by natural ecosystems, setting the theoretical basis of IE in systems-science. He defined IE as,

'… [I]ndustrial ecology intend[s] to facilitate the evolution of manufacturing from Type I [linear] to Type II [semi-cyclic] or Type III [cyclic] behaviour by explaining the interplay of processes and flows and by optimizing the ensemble of considerations that are involved.' (Graedel, 1994, p. 26)

This definition brings to mind the famous diagram of a CE system from the report by Ellen MacArthur Foundation (EMF), with the feedback loops in the biological and technical systems (*Towards the Circular Economy (Vol 1)*, 2013, p. 58). Just like IE, the concept of circularity has been around long before (Boulding, 1966) it received global attention when EMF used it as a spearhead. The United Nations Environment Program defined the core logic behind CE as decoupling of growth rates from the rates of resource consumption (resource decoupling) and environmental degradation (impact decoupling) (UNEP, 2011). Sharing the same theoretical grounding, CE finds a hospitable host in the field of IE.

Where CE is gaining popularity as a more practical practice by businesses, IE still retains a broader academic interest. According to Erkman (2001),

'Industrial ecology focuses on the long-term evolution of the entire industrial system, and strives to reach its objective by using a dual approach: a rigorous one in terms of theory (scientific ecology) and an operational one (prescribing economically viable concrete steps).' (Suren Erkman, 2001, p. 536)

Stemming from the *rigorous* approach, Nikolic notes that IE as a field of study examines the evolution of the interconnected environmental, social, economic, and technical systems for solutions toward sustainability (Nikolić, 2015). Hence, Nikolic emphasised the connection of industrial ecology with the study of complex systems where sustainability is a system behaviour that emerges because of the interaction of different actors, within and across, different sectors, at varying temporal and spatial scales. The *operational* aspect of IE has already been mentioned in the text by Graedel, who called it *applied IE* and defined it as the study of driving factors influencing the flows of selected materials among economic processes (Graedel, 1994). Closely related to the operational aspects of IE, Erkman also defined four challenges faced by human population that must be met within the framework of IE. These are,

1. *Waste and by-products must systematically be exploited* (through eco-industrial networks);
2. *Loss caused by dispersion must be minimized* (through redesigning chemical products to reduce loss);
3. *The economy must be dematerialized* (through new business models that replace ownership of product with services that fulfill the consumer needs); and
4. *Energy must rely less on fossil hydrocarbons* (through renewable sources or by carbon capture and storage) (Suren Erkman, 2001, pp. 533–534).

The first challenge finds its solution in reimagining a society without waste, which is also the first guiding principle of CE, defined in the publication of EMF; *CE aims to design out waste* (*Towards the Circular Economy (Vol 1)*, 2013). This branch of IE focuses on material exchanges and the relating business practices, where waste is systematically reduced and it replaces raw materials in industrial processes. When different industries, and, sometimes, their neighbouring municipalities, collectively strive for resource and energy efficiency, this results in cooperative management of resource flows between businesses and engagement of traditionally separate entities in a collective approach to competitive advantage, otherwise termed as Industrial Symbiosis (Lowe & Evans, 1995) (M. R. Chertow, 2000a).

The second challenge that IE aims to meet is the redesigning of products. Concepts like cradle-to-cradle approach and biomimicry have evolved in the field of product design to answer this challenge. The third challenge requires innovation in the business arena and receives significant attention under the banner of CE. The fourth challenge, which is set in climate change has received the most academic and political attention but remains the most pressing problem of our time. This is also the third guiding principle of CE defined by EMF; *Energy used for the technical cycles should be renewable by nature* (*Towards the Circular Economy (Vol 1)*, 2013). Even though the technological solutions exist, the shift in the energy systems from fossil based to renewables has faced challenges at the institutional level. The techno-institutional complex, concept introduced by Unruh (2000), has evolved to support technologies and policies that are embedded in use of fossil fuels (Unruh, 2000). Thus, the last challenge requires a system transition and the branch of IE dealing with it builds on the theory of complex systems, also mentioned by Nikolic (Nikolić, 2015). These definitions frame this thesis firmly in the field of IE and CE.

CE can be divided into two categories: Narrow CE, which refers to reduction of wastes and resource recovery and, Broad CE, which covers all the socio-economic activities including consumption behaviour, corporate attitude and political mind-set (Zhou, 2006). Again, the dual approach of incremental improvements and system-level changes is evident in this categorisation. It is beyond the scope of this thesis to discuss which strategies compare better against the others. However, the categorisation helps to frame the thesis into two major sections; one focusing on incremental improvements in process industries and the other focusing on radical change, or transition of energy system to renewable sources.

As the field of study is established for this thesis, the next section deals with the academic theories that help shape the interventions to bring a sustainable change in the current economic and industrial practices.

1.2 UNDERSTANDING COMPLEXITY AND SYSTEM TRANSITION

In 1968, the Club of Rome called the human predicament, as the 'world problematique' [1, p 10]. These problems are of political, environmental, social, economic, psychological and cultural nature, and most importantly, they interact. Despite the recognition of the world problematique for a long time, these problems persist and perhaps always will. The Club of Rome isolated the main reason behind mankind's failure in tackling the world problematique as the narrow modus operandi of humans, which focuses on individual items of the problem without acknowledging that the whole is more than the sum of its parts (Meadows et al., 1972).

This 'largeness' of the problem has been described as an attribute of complex systems. Studying complex systems is not aimed at control of the system, that is far too ambitious, but to understand the working of the system so to devise meaningful policies (Vemuri, 2014). With the same objective, academics in the field of (technology) innovation and transition studies have presented a number of theories based on different case studies to explain and (eventually) bridge the gap between short-term interests and long-term objectives of the human society (Frantzeskaki, 2011; D. I. F. W. Geels, 2005; F. W. Geels, 2002; R. Kemp, 1994; Köhler et al., 2019; Patterson et al., 2017; Rotmans et al., 2001).

The following section deals with the overview of complex systems and system transition, and the link between these fields of study and this thesis.

1.2.1 Complex Systems

As a field of study on their own, complex systems have only emerged in the 1970s (Vemuri, 2014), however the complex systems have been a part of mathematics, physics, ecology, computer science, and evolutionary biology (Chan, 2001) since the identification of nonlinearity. Complex systems, for the sake of ease to explain, sometimes are referred to as large systems, as they are made up of nested systems. Although, in theoretical terms, this 'largeness' is not the defining property of a system to be complex, it is indeed the complexity of behaviour of a system (Vemuri, 2014). Bar-Yam (2002) defined complex systems as a discipline, "… as a new field of science studying how parts of a system and their relationships give rise to the collective behaviours of the system, and how the system interrelates with its environment" (Bar-Yam, 2002).

When describing complex systems, one is inclined to use 'complexity' as a qualifying feature of a complex system. However, complexity is a relative notion. What is complex to one person is not to another, likewise, the scale of observation also affects the definition of complexity. Human body is a complex system that is made up of nine organ systems. However, at the scale of an individual, one human is not complex. Hence, defining complex systems requires looking at a number of features of the system (Cilliers, 2002, p. 2). Based on Bar-Yam's encyclopaedia article, Cilliers' and Randall's books, complex systems share the following features (Bar-Yam, 2002; Cilliers, 2002; Randall, 2011).

Complex systems comprise of many interacting and interdependent parts or even embedded complex systems. These interconnected parts or networks may show strong or weak local connectivity, which defines how change may propagate through the system. These relationships are not fixed which leads to the dynamic nature of complex systems. Another major feature of complex systems is non-linearity of effects. It means that the linear increase of inputs does not result in a linear increase of outputs. This can result in a small perturbation having a large affect. This non-linearity is caused by the feedback loops of relationships in complex systems that influence change in behaviour of the system's parts by either accelerating or slowing it down. This non-linearity of effects is one major factor that distinguishes complex systems from complicated (linear) systems. This leads to intrinsic impossibility to predict the future state of complex systems as an infinite number of possible future scenarios can occur even by small changes.

The ability of complex systems to change is a result of self-organisation of its parts. Self-organisation compels complex systems to show emergent behaviour, which brings to point the relevance of scale of interconnectivity. For example, the behaviour of birds flying in a flock, social behaviour of termites in mound building, etc. can only be observed when the whole is observed rather than the individual bird or termite. This observation of the *whole* to define the behaviour of the system, rather than the study of individual parts of the system, defines the second difference between complex and complicated systems. Alternatively, it can be said that complex systems cannot be broken down into constituent parts, as this reduction of complexity robs the complex system of its properties. Complex systems are open systems and are impacted by their environment, hence making it difficult to delineate their boundaries. Complex systems have a memory (hysteresis). This means that the prior state of the system has an impact on the future states.

Furthermore, the complex systems that evolve over time are called complex adaptive systems. This evolution has been likened to the evolution of species as described by Charles Darwin. Just as through time the organisms have evolved from unicellular to complex organisms, a complex system also adapts to the changing environment over time. The examples of complex adaptive systems include the biosphere and the ecosystem, the brain, the immune system, the cell, social insect colonies, the stock market, the economy (Randall, 2011), and industrial networks in eco-industrial parks, etc.

A particularly useful discussion of complex adaptive systems is found in the work by Arthur and colleagues (1997), who identify six properties that characterize any economy:

dispersed interaction, the absence of a global controller, crosscutting hierarchical organization, continual adaptation, perpetual novelty, and far-from-equilibrium dynamics (Arthur et al., 1988) as cited by (Levin, 1998). John Holland, who coined the term adaptive nonlinear networks to describe systems that satisfy Arthur and his colleagues' six characteristics, identifies four basic properties of any complex adaptive system: aggregation, nonlinearity, diversity, and flows. Within the field of IE, Chertow and Ehrenfield use the concept of complex adaptive systems to define the development stages of an eco-industrial park (M. Chertow & Ehrenfeld, 2012). Their work will be revisited in the following sections of this chapter.

Modelling complex systems is bound to have its limitations. As all models are built by simplifying reality, in a system that loses its properties when simplified, modelling becomes a challenging task. However, as mentioned earlier, the study of complex (adaptive) systems is hardly carried out to practice control rather the aim is to understand the workings of the system and gain enough information to design useful policies. There are three different sets of tools for modelling complex systems, as defined by Chan: aggregation of models, test problem generation, and agent-based simulation (Chan, 2001). The modelling technique that is most relevant to this thesis is agent-based simulation, which serves as a platform for imitating the nonlinear characteristics of real-world complex systems (Chan, 2001).

System scientists are fascinated by complex systems but how does the understanding of complex (adaptive) systems help the transition to a sustainable world. Our global energy system is under transformation from a fossil-based to a renewable energy based one. Policy makers are concerned with tackling a phenomenon that is both complex and adaptive. Directing this transforming energy system to a more sustainable, (technologically) inclusive, and low-carbon future requires a better understanding of its mechanisms. This is precisely the topic of the following section.

1.2.2 System Transition via Multi-level Perspective

"A transition can be defined as a gradual, continuous process of change where the structural character of a society (or a complex sub-system of society) transforms", Jan Rotmans, René Kemp and Marjolein van Asselt stated in their article *More evolution than revolution* (Rotmans et al., 2001, p. 16). The authors explained this transition as a multi-dimensional phenomenon that spreads over multiple domains. Meaning, that it involves changes in technology, the economy, institutions, behaviour, culture, ecology and belief systems. As these domains interact and as independent developments start to occur in these domains, the resulting effects reinforce one another and the change is accelerated. Once the speed of change decreases, the system starts to stabilise, and a new equilibrium occurs. These processes are defined as the dynamics of system transition. This definition can be compared to the features of complex adaptive systems explained above.

The widely cited and most relevant theory for system transition in function-oriented systems, especially energy and food production, is based on defining the different levels of a system in relevance to technological innovations. The Multi-level perspective (MLP) refers to the distinction that is made between the three levels for diffusion of an innovation in the society (Rip & Kemp, 1998). The three levels of the MLP are: The Niche level (micro), the Regime level (meso) and the Landscape level (marco), as described by Rip and Kemp (1998) (Rip & Kemp, 1998).

Niche level:

The niche level is the micro level where radical (technological) innovations arise. It should be seen as the place where variations and innovations that cannot find development space within the existing socio-technical regime, can develop. Niches do not arise from nowhere but are "created" on the basis of promises, perspective on new applications or in the hope of discovering a specific problem to solution (the novelty).

Regime level:

The Regime (or socio-technical regime) level refers to the conventional manner in which a social function is fulfilled and styled. When the term Regime was first introduced by the authors of (Nelson & Winter, 1977; Winter & Nelson, 1982) it was only meant for defining the technological regime. It was referred to, by technicians as shared cognitive routines that lead to specific technological development. The term was widened by Rip & Kemp and explained as the rule-set or grammar embedded in a complex of engineering practices, production processes, technologies, product characteristics, skills and procedures, ways of handling relevant artefacts and persons, ways of defining problems - all of them embedded in institutions and infrastructures' (Rene Kemp & Rip, 1998).

This new definition of the regime introduced social aspects and resulted in the concept of a socio-technical regime. The concept of socio-technical regime expresses the broader social impact of technological change. According to this definition of the regime, the rules of the regime are not only in the minds of the technicians, as implicitly suggested by Nelson and Winter (Nelson & Winter, 1977; Winter & Nelson, 1982) but rules are embedded in procedures, structures, processes and products. The direction of the development of the technology is not only based on the influence of the technicians, but also on the influence of the consumers or policy makers, to name a few.

Landscape level:

The Landscape (or socio technical landscape) level forms the background against which the developments in the regime and niche level occur. Rene & Kemp introduced the term 'socio technical landscape' in meaning, as it is used within the MLP. They described this term as: "The socio technical landscape is a landscape in the literal sense, something around us that we can travel through; and in a metaphorical sense, something that we are part of, that sustains us [...] The two senses or socio-technical landscape are inherently linked" (Rene Kemp & Rip, 1998, p. 334).

Geels and Kemp (2000) widened the concept of Landscape further. They describe the sociotechnical landscape as the context for regimes and niches. These are developments that are not directly part of the regimes and niches, but it does have influence on them. They are deep-seated structural trends outside the direct influence of niches and regime actors. These trends usually develop relatively slow. Developments in the landscape do not define the actions of regime actors in absolute terms, but they make certain actions easier or harder than others.

> "Every system that changes involves irreversible processes." (Dam et al., 2012)

The time scale of changes in the niche level is the smallest while regimes are more stable and hence the changes occurring here are slower. Regimes encompass the widely held beliefs, rules, shared assumptions and practices that guide public policy, mostly meant for optimising rather than transforming a system (Rotmans et al., 2001). Hence, regimes can be viewed as a barrier to innovation. However, once a new technological system proves successful the regime plays an enabling role. This behaviour has been attributed to path dependence and ultimately a lock-in of a society in a particular technological system. Path-dependence or sunk costs, also known as high switching costs (Economides, 1996) and lock-in, is embedded in the idea that past decisions influence future decisions to be made. This reinforcing behaviour of the regime has been used by Unruh to define the carbon lock-in our world is facing and how the global society can break away from it (Unruh, 2000, 2002).

According to the MLP, governments and businesses striving to bring a change in the fossil fuel-based socio-technical regime can only rely on system improvement, contrary to all climate pacts to reach for climate neutrality. The early work on MLP also falls short in considering the effect of technology users (consumers) on the system transition and lacks in appreciating the agency of different actors. These and many other critiques on MLP have resulted in rethinking the MLP, while some have been effectively answered (F. W. Geels, 2011) others have left room for new theories to be developed and the MLP to be improved (Genus & Coles, 2008).

In light of the literature presented on complex (adaptive) systems and system transition the importance of incremental changes cannot be ignored, especially when considering the global commitment to curbing climate change. In light of this knowledge, section 3 deals with the improvements in energy and material utilisation processes in industry through industrial symbiosis. While, the more disruptive changes in the existing energy system are the topic of section 4 of this chapter, where the MLP is used to frame the diffusion of wind power in the existing energy grid.

1.3 INCREMENTAL CHANGES AND INDUSTRIAL SYMBIOSIS

Already in the late ’80, Frosch and Gallopoulos (1989) recognised the need for a new approach to model industrial activities (Frosch & Gallopoulos, 1989). For the first time they introduced the concept of industrial ecosystem comparing industrial agglomerations to natural systems. Since then, this concept has been further explored and increasingly studies have been carried out using a systemic approach to define the characteristics and dynamics of such agglomerates. The basic assumption of such assimilation is that as in natural systems also in industrial ecosystem waste and by-products of one process can be used as inputs for other processes, in this way the resource used are optimised and no waste is produced (Lowe & Evans, 1995). The motivation is to bring industrial performance within the carrying capacity of the planet.

However, the most widely quoted example of an industrial ecosystem remains to be Kalundborg (Denmark), which did not develop from a conscious effort to bring waste levels down for the purpose to stay within planetary boundaries. Jorgen Christensen (VP of Novo-Nordisk) says, *’At the time we were just doing what was profitable and what made sense’* (Lowe & Evans, 1995, p. 49). It was the economic benefit that lay in the symbiotic activities between the co-located businesses that resulted in making Kalundborg a beacon among academics working in the field of IE.

The spontaneous evolution of Kalundborg inspired public authorities to recreate the situations that resulted in Kalundborg’s eco-industrial park in other places. Chertow emphasised the existence of other such examples in her paper *Uncovering Industrial Symbiosis* (M. R. Chertow, 2007). Chertow’s work shows that planned eco-industrial parks have failed mostly in North America and Europe. The emphasis on technical aspect of symbiosis – the matching of flows – narrows the field of possible recruitment targets, adding rigidity to the system that needs to be adaptable (M. Chertow & Ehrenfeld, 2012).

Industrial symbiosis, by itself, can be seen simply as a more efficient use of energy and materials (M. Chertow & Ehrenfeld, 2012), hence the improvement in the current business practices that industrial symbiosis promises is of incremental nature. However, when concerns about unsustainability become a more dominant driving force, then eco-industrial networks will have an important role to play in our approach toward a sustainable world.

1.3.1 Defining Industrial Symbiosis

Boons et al. (2017) acknowledged the problem of equivalence in the concepts of industrial symbiosis (Boons et al., 2017). They explicated that industrial symbiosis, as a concept, have differing definitions depending on the research question of the researchers observing the phenomenon of industrial symbiosis and also on the empirical data that the researchers have (Boons et al., 2017). There are many definitions of industrial symbiosis in literature. Here the most cited ones are mentioned, leading to the one that fits the objectives of this thesis.

Industrial symbiosis has been defined and redefined in the IE literature. Chertow (1999 & 2000) proposed the definition of industrial symbiosis as the material centric activities that emphasized the exchange of wastes between co-located industries, providing competitive advantage to the participants (M. R. Chertow, 1999, 2000a). Personnel, equipment and information sharing were mentioned as less non-tangible benefits of industrial symbiosis. Chertow et al. (2007) identified three motivations for resource exchange: (1) By-product reuse—the exchange of firm-specific materials between two or more parties for use as substitutes for commercial products or raw materials. (2) Utility/infrastructure sharing—the pooled use and management of commonly used resources such as energy, water, and wastewater. (3) Joint provision of services—meeting common needs across firms for ancillary activities such as fire suppression, transportation, and food provision.

This definition, although closer to the original intent of IE, narrowed the focus of industrial symbiosis to location proximity (M. R. Chertow et al., 2008). Chertow also described the three levels of IE; the firm level, the inter-firm level, and the regional or global level (M. R. Chertow, 2000a, p. 315). Chertow identified that industrial symbiosis is observed at the inter-firm level, however, later work has shown that industrial symbiosis linkages can surpass regional boundaries, depending on the economic value of the materials being exchanged (Jensen et al., 2011). This leaves room to improve upon the three levels of IE that Chertow proposed.

In 2012, Lombardi and Laybourn, took to redefine industrial symbiosis as a tool for innovative green growth and proposed that industrial symbiosis engages diverse organizations in a network to foster eco-innovation and long-term culture change (D. R. Lombardi & Laybourn, 2012). Other definitions have also proposed to include exchange of information as an activity that can qualify as an industrial symbiosis(Schwarz & Steininger, 1997). These definitions freed industrial symbiosis of the geographic proximity constraint. Other disconcerting aspects of the industrial symbiosis definition proposed by Chertow (2000) remain open to discussion till today: Whether same ownership of different industrial processes mean these are same entities? Does the exchange between different companies but similar industrial sector mean it is not an industrial symbiosis? Would exchange of slag between steel and cement be considered industrial symbiosis, although it has been carried out for almost 30 years (Van Oss & Padovani (2003) as cited by (D. R. Lombardi & Laybourn (2012)).

These questions led to broadening the scope of industrial symbiosis in the work of Duetz (2014), who defined industrial symbiosisas a flow of underutilized resource(s) (comprising substances and/or objects and /or energy), from an entity which would otherwise, discard them, to another entity which uses them as a substitute for new resources (Deutz, 2014, p. 5). Deutz, rightfully so, pointed out that environmental, economic or social benefits that have been conclusively defined as intrinsic to industrial symbiosis are in fact contingent benefits. The real motivation behind industrial symbiosis lies in resource efficiency and the need to distinguish innovative activities for resource efficiency from business as usual. The term innovative here describes the context of the activities, which the participating agents alter to improve the efficiency of resource use, whereas, business as usual refers to the sale of a good for which it was intended.

Following the reasoning of Deutz (2014), in this thesis, industrial symbiosis is defined as a means to resource efficiency and not the end in itself (Deutz, 2014). The questions that have occupied the academics in IE regarding the one – all-inclusive – definition of industrial symbiosis, does not claim more attention in this thesis. The focus here is on the work carried out in the context of the EPOS project, where the entities are different industrial sectors and their neighbouring districts. The activities that qualify as industrial symbiosis are the ones that entail efficient utilisation of previously underutilised resources and capacities. Physical material exchanges do not limit the industrial symbiosis activities in this dissertation neither does geographical proximity. The considerations that have been respected in defining an activity as an industrial symbiosis are: 1) Activities that involves more than one EPOS entity. 2) Activities that ensure energy and resource efficiency at a system level, excluding recycling. 3) An innovative approach to using secondary resources (all resources that are put to use rather than being discharged or discarded) as compared to business as usual.

Industrial symbiosis has emerged in different forms in different parts of the world. In China, it has manifested as part of a top-down approach, whereas in Kalundborg (Denmark) it emerged in a bottom-up style. Authors have elaborated on different perspectives on industrial symbiosis and the different mechanisms that are observed in the evolution of a symbiosis. In the following two sections, I present industrial symbiosis evolution and dynamics with the intent to reach a methodology that will help classify the industrial agglomerations that form part of the case study I.

1.3.2 Industrial Symbiosis as Complex Adaptive System

Industrial symbiosis involves, physical exchange of materials, energy, water, and by-products, as well as, sharing social tactics at the firm and multi-organisational level (Ruiz Puente et al., 2015). This inter-firm cooperation (M. R. Chertow, 2000a; D. R. Lombardi & Laybourn, 2012; Van Eetvelde, Delange, et al., 2005) enables businesses to strive for a collective economic and ecological benefit that is greater than the sum of individual benefits each company can achieve [10, 4]. As discussed before, the field of complex adaptive systems is a study of how complicated structures and patterns of interaction can arise from disorder through simple but powerful rules that guide change (Levin, 1998). The dynamic nature of industrial symbiosis and the presence of diverse agents in an industrial ecosystem, whose interaction results in a behaviour of the system (sustainability, as mentioned above by Nikolic) provides ample ground to qualify these ecosystems as complex adaptive systems (M. Chertow & Ehrenfeld, 2012; Levin, 1998).

Industries or businesses usually do not engage with each other on matters that are strategic for their survival, except when common problems or goals arise, which creates dependency between the actors (Baas & Boons, 2004a). For strategic matters, industries are part of other networks such as the multi-national firms or the global product chain (Baas & Boons, 2004a). This means that evolutionary processes lead to a general increase in complexity of the system. Complexity increases when the variety (distinction) and the dependency (connection) of part of the system increase in space and/or in time (Mat et al., 2017). Evolution of the system thus produces differentiation and integration (Mat et al., 2017).

Chertow and Ehrenfield defined a three-stage model of the evolution of industrial symbiosis, drawing on sources of Shwarts and Steininger, Baas and Boons, and their own work (Baas & Boons, 2004a; M. Chertow & Ehrenfeld, 2012; Schwarz & Steininger, 1997). These stages are sprouting, uncovering, and embeddedness and institutionalisation.

1. Sprouting

Sprouting is identified by exchange of resources for a random number of reasons and are termed as *kernals of industrial symbiosis* (coined by Chertow, 2007 (M. R. Chertow, 2007)). These linkages are disordered and come and go just as traditional trade linkages rise and fall along the supply chains of firms, even if they produce positive environmental externalities. Mainly, due to the reason that these exchanges are not observed or happen without intent. But in some cases, positive network externalities influence the decision analysis of the firms to positively assess future exchanges. At this stage, there are three kinds of costs related to industrial symbiosis.

a) Search costs (costs of locating information about opportunities for exchange)

b) Negotiation costs (costs of negotiating the terms of the exchange)

c) Enforcement costs (costs of enforcing the contract)

These transaction costs, however, can be small in comparison to costs created by sufficiently stringent regulatory requirements to reduce various forms of pollution. Information and Communication Technology (ICT) tools can reduce the search costs for industrial symbiosis. European funding schemes have focused on incentivising the development of IT tools for industrial symbiosis in the past two decades. An assessment of the development and success of these incentives is presented in a journal article by the author of this thesis (Maqbool, Mendez Alva, et al., 2019).

2. Uncovering

During this stage positive environmental externalities of the network(s) become well known. An actor whose focus is beyond the private transactional network is usually observed to carry out this stage. Baas and Boons (2004) associate this stage with regional learning where both goals and range of membership broaden (Baas & Boons, 2004a). This entity could be public or private, formal or informal, elected or appointed. The important point is that a formal institutional form appreciates and expresses the public values that have been newly created and articulated. This gives them sufficient weight to successfully compete with other norms within firms—especially the pervasive norm of profit maximisation—such that these values can coexist. This appreciation leads to the network that has developed to continue to thrive and grow. This stage can be compared to the self-organising behaviour of complex system.

3. Embeddedness and institutionalisation

In addition to self-organisation, further expansion of the network takes centre stage driven by an institutional entity created at an early stage that becomes more deeply established during this stage. Embeddedness occurs over time. On the positive side, it can continually reduce transaction costs and uncover new benefits not considered in earlier economic calculations, although the possibility also exists that relations could become insular and thus inhibit innovative activity (Granovetter, 1985). Enforcement costs are generally lower among familiar transacting parties.

Chertow and Ehrenfield have elaborated that these stages are discontinuous, the progress across them is nonlinear and cannot be predicted. Standard environmental economic theory also suggests that, in some cases, public assistance may be needed to offset the private costs to the firms involved in the symbiosis network (M. Chertow & Ehrenfeld, 2012).

The three-stage model presented above points to regulation and other mechanisms to achieve the needed offset of barrier removal costs. Also, identifying the typical industrial symbiosis dynamics will also help in devising better mechanisms to support industrial symbiosis. In the following section I present the seven industrial symbiosis dynamics proposed by (Boons et al., 2017).

1.3.3 Industrial Symbiosis Dynamics

Other research by Boons and colleagues have focused on the dynamics of industrial networks, that involve flows between agents, the evolution of activities and the actors, the system level effects of learning and sustainability outcomes.

Time has always been an important factor in IE and industrial symbiosis is appropriately explained as a dynamic process, rather than a static phenomenon (Boons et al., 2011, 2014; Boons & Spekkink, 2012; M. Chertow & Ehrenfeld, 2012; Schwarz & Steininger, 1997; Spekkink, 2017). Baas and Boons explained the evolution of industrial ecosystem through three stages, for brown fields: 1) Regional efficiency; independent resource efficiency activities emerge that make use of the existing win-win situations. 2) Regional learning; diverse actors join in the systems and share knowledge based on trust and acknowledgement and extend the scope of sustainable activities. 3) Sustainable industrial district; when actors define an evolving vision of sustainability and plan their activities accordingly (Baas & Boons, 2004a). Whereas for green fields, a stage of *selection* precedes these three stages.

The evolution of industrial symbiosis has been described with the help of existing literature and scientific fields such as, geographic economy (Paul E. Krugman) and economic clusters (Micheal E. Porter). While discussing the development of industrial symbiosis networks in Puerto Rico, Chertow and colleagues drew similarities between the enhanced economic activity between co-located firms, based on the work of Krugman (M. R. Chertow et al., 2008; Krugman, 1991). Similarly, the widely cited work on cluster economics has also been used in the same publication to define the economic advantages of similar companies based on the concept of clusters defined by Porter (1998). He defines clusters as geographic concentrations of interconnected companies and institutions in a particular field (Porter, 1998). Thus, the advantages of sharing knowledge, expertise, and resources to improve economic competence has been around before the interest in industrial symbiosis. The widely cited concept of economic cooperation and competition (coopetition) by Porter also provides basis for research on symbiotic networks.

Since industrial symbiosis not considered as an end in itself rather a process, it is best to study these processes in a context that helped shape them. Hence, while studying the industrial symbiosis dynamics in the clusters, I followed the categorisation by Boons et al. (Boons et al., 2017). Boons et al (2017) proposed seven typical pathways through which industrial symbiosis unveils. They referred to these pathways as the industrial symbiosis dynamics. These seven pathways or sequence of events are distinguished based on four characters; namely, 1) the initial actor(s), 2) the motivation of the initial actor(s), 3) the actions that follow to formulate an overall storyline, and 4) the typical outcomes. Following is a brief description of these seven dynamics.

1. Self-organisation

Self-organisation occurs when an industrial actor looks for a partner to engage in symbiotic activities due to preconceived benefits and it results in contractual agreements being made and the industrial symbiosis being operational. Such self-organisation results in either of the three typical outcomes, an agglomeration, a hub-and-spoke network, or a decentralised network. The most famous example of this dynamic is Kalundborg industrial cluster (M. Chertow & Ehrenfeld, 2012; Ehrenfeld & Gertler, 1997; Jacobsen & Anderberg, 2004).

2. Organisational boundary change

When an industrial actor changes its activities from vertical integration to outsourcing, the existing linkages now cross organisation boundaries and hence are classified as industrial symbiosis. Such examples are found in chemical clusters, where businesses change hands and the symbiotic linkages remain. The detailed example of this dynamic is found in British sugars that explains the diversification of activities (Short et al., 2014).

3. Facilitation – brokerage

Facilitation-brokerage is defined as a public or a private third-party organisation setting up a market for industrial symbiosis and industrial actors engaged in industrial symbiosis through the broker's facilitated market system. This may result in a one-off network of symbiotic exchanges. The National Industrial Symbiosis Program (NISP) in UK can be identified with this dynamic in the early stages of implementation (Mirata, 2004; Paquin & Howard-Grenville, 2012).

4. Facilitation – collective learning

Similar to the facilitation brokerage in its characteristic of broker facilitated market system, this dynamic is particularly focused on mimicking industrial symbiosis examples that are modified to match the regional context of the actors. The industrial actors and the broker engage in a collective effort to learn and develop a symbiotic network. NISP UK started out as a simple brokerage system. Later International Synergies, the industrial actors, and the government have used the learning from NISP to engage in more strategic and goal-oriented processes. This dynamic and the previous one can switch back and forth, which was the case in NISP UK (Paquin & Howard-Grenville, 2012).

5. Pilot facilitation and dissemination

Pilot facilitation and dissemination occurs when a facilitator aims to mimic industrial examples that are translated to the regional or national context of some selected collocated industries. The learning of the pilot projects helps to refine the concepts and the facilitator disseminates the industrial symbiosis concepts to other groups of collocated industries. This results in a diffusion of industrial symbiosis concept among clusters.

6. Government planning

When the governmental actor(s) aim to mimic industrial symbiosis by translating it into the national and regional policies. A plan is developed to stimulate or enforce the policy instruments that also monitor the progress. The learning is fed back into the policy that ensures the continuation or renewal or conclusion of the plan. This type of industrial symbiosis dynamics are widely reported in Asia, especially in China (Geng et al., 2009; Shi et al., 2010; L. Zhang et al., 2010).

7. Eco-cluster development

When governmental and/or industrial actor(s) plan to develop eco-industrial clusters as part of an eco-innovation strategy. Other stakeholders voluntarily participate in the process. The result could be the development of a brownfield or a greenfield, or the formation of an innovation cluster. Examples are noted in the Netherlands, where the government supported the development of eco-clusters with the aim to boost bio-based economy (Boons & Janssen, 2004; Boons & Spekkink, 2012).

It has to be mentioned that these seven categories are not mutually exclusive in one industrial symbiosis case study. It could be that an industrial park shows one dynamic at one time and then changes to another. industrial symbiosis case studies dominated the IE literature and this thesis also includes industrial symbiosis case studies in chapter 3. These seven categories are used to refine the analytical research and provide more substance to narrative analysis of the presented case studies. Furthermore, to provide a connection to sustainability with the industrial symbiosis cases, the matrix of sustainability embedded in the objectives of local agenda 21 presented by Baas and Boons is also used in the analysis. This matrix is provided in Table 1-1.

Table 1-1: Modes, characteristic features and canons of sustainability

Mode of sustainability	Characteristic features of 'modes of sustainability'	'Canons of sustainability': integration of economic, social, environment
Very strong	New community structures Community-led initiatives become the norm	Isolated pointers to industrial complexes based on 'ecological' flows
Strong	Local initiatives as part of community growth Community involvement	Genuinely holistic thinking starting to emerge in some quarters of local government
Weak	Wider public education for future visions Round tables, stakeholder groups	Policies for industry generally reflect the 'weaker' end of the sustainability spectrum
Very weak	Lip service to policy integration Problems of including business in dialogues Minor tinkering with economic instruments Faint social awareness and little media coverage	Department silos still strong Implications that LA21 fosters 'business as usual' despite rhetoric

The understanding developed on the basis of industrial symbiosis dynamics and the three-stage model of industrial symbiosis development as a complex system helped in the case studies that formed part of the EPOS project. The EPOS project and the work that was carried out under its flagship are introduced in the following section.

1.3.4 Case study: Industrial Symbioses in EPOS

In 2015, a consortium of five process industries, five SMEs, and two academic institutes proposed the EPOS project. The industrial interest in the project lay in the development of a methodology and software for supporting energy and resource efficiency, along with the opportunity to explore mutually beneficial activities between the selected sites of the industrial partners. The academic interest lay in the testing and improvement of the tools developed by the two institutes; first, an engineering tool for the design and analysis of integrated energy systems, second, a methodology set in the objective to measure and monitor the effect of cluster management on the concerted actions of the companies (Van Eetvelde, 2017). The latter is built around the premise that non-technological aspects of industrial symbiosis are as – if not more – important when assessing the feasibility and impact of symbiotic activities. These non-technological aspects are grouped under five domains; *Legal, Economic, Spatial, Technical, and Social* (Van Eetvelde, Delange, et al., 2005) and the method is termed LESTS.

The boundary of the case study is limited to the agglomerates of industries in four countries and five locations, as shown in Figure 1 1 (on the next page). For parsimony of words, the term cluster is used to identify each of the locations in case study I. The widely accepted use of the word refers to similar companies and related institutions without a defined geographic boundary. Here a cluster refers to industrial sites belonging to different sectors, all partners of the EPOS project who volunteered to be assessed for their potential to engage in industrial symbiosis. The benefit is two-fold, first; it helped avoid sharing sensitive information between competing industries, second; similar sectors produce similar wastes and require similar inputs, but dissimilar sectors can have higher chances of finding matches between wastes and energy streams. This is called cross-sectorial industrial symbiosis.

These industrial clusters are located in Poland, France, and UK, while two district heating networks are located in France and Switzerland, each. The industrial sectors or districts include the following combination of partners in each geographical location.

1. The Rudniki cluster in Poland consists of the cement (Rudniki) and minerals (Jasice and Romanowo) and steel (Krakow) plants.
2. The Lavéra cluster (France) is comprised of chemicals (Lavéra) and steel (Fos) plants.
3. In Humber cluster (UK) is made up of minerals (Melton) and cement (South Ferriby) and chemicals (Hull) plants.
4. Steel (Dunkirk) represents industry in Dunkirk cluster (France). The steel plant engages with the city of Dunkirk in a district heating network (DHN).
5. City of Visp (Switzerland) has a district heating and cooling network fed by a biotechnology company.

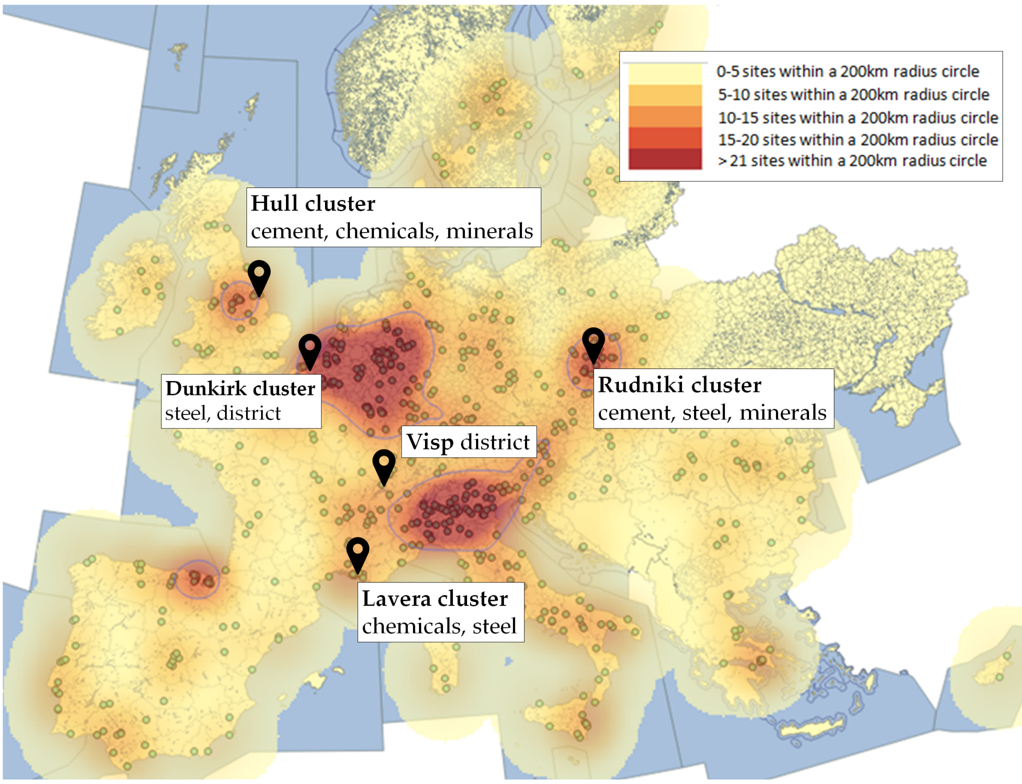


Figure 1-1: Map of the European industrial symbiosis hot spots and the locations of industrial symbioses in the case study (adapted from (Strane Innovation SAS, 2016))

Each of the industrial clusters was assessed for their existing and potential industrial symbioses. The method for the content analysis was divided into five aspects according to LESTS and conclusive remarks about the dynamics of symbiosis were drawn on the basis of the work of Boons et al. (2017), supplemented by the three-stage development process of industrial symbiosis by Chertow and Ehrenfield (2011). The methodology is defined in detail in Chapter 2. Furthermore, the potential industrial symbioses were proposed to the industries complemented with a numeration of their Strengths, Weaknesses, Opportunities, and Threats (SWOTs). All the symbiotic opportunities that are proposed under this study focus bring two or more process industries together. Where no potential symbiosis could be found, the waste streams were valorised to replace primary raw materials or energy sources so that the industries could look for potential partners outside of the aforementioned sectors.

The case study is presented in two consecutive chapters in the thesis (Chapter 3 and Chapter 4).

1.4 TRANSITION TO RENEWABLE ENERGY

Globally we are transitioning to an energy system that is dependent on the renewable energy. In 2017, with 17% contribution of renewables in the total energy needs, EU was well on the way to achieve the 2020 target of 20% renewables (European Commission, 2017). As the EU Renewable Energy Directive aims to increase this number to 32% in 2030 (European Commission, 2018), considerable investments and infrastructural changes are needed in the European member states to transition to renewables energy systems.

As introduced above, transitions involve a range of possible development paths, whose direction, scale and speed government policy can influence, but never entirely control (Rotmans et al., 2001, p. 16). The German government has shown the most ambitious of these efforts, in the form of Energiewende, a set of plans to achieve to a low carbon, environmentally sound, reliable, and affordable energy supply (Tews, 2013) as referenced by (Frondel et al., 2015). This transition does not come without uncertainty and its own set of challenges. The German Energiewende has been questioned for its toll on the poor households as it increases the prices of electricity (Frondel et al., 2015) and for its fairness of cost and benefit distribution among different actors in the power system (Cludius et al., 2014). The inherent uncertainty and variability of the wind and solar power technologies results in a high friction – technically, financially, and operationally – when integrating them in the existing energy system.

Rotmans et al. (2001) have narrated the evolution of energy system in the Netherlands from coal based to natural gas. The authors emphasised how a government can exert guidance to changing a regime by subsidising specific technologies, supporting research and development of the same technology, and supporting public awareness campaigns (Rotmans et al., 2001). After decades of supporting natural gas, the Dutch government is now committed to transitioning the energy system to a renewable based one (van Leeuwen et al., 2017), mainly because of the adverse climatic effects of the fossil fuels and partly because of the geologic impact of prolonged gas mining in the Northern parts of the country (Osborne, 2019).

It is also mentioned in literature regarding system transition and the MLP that different regimes (science regime, economic regime, technology regime, etc.) interact in complex relationships. Hence, only incentivising technologies based on renewable energy through subsidies is not enough to bring about a transition; consumer behaviour, social norms, and markets also play a crucial role in defining the success of renewable energy technologies. Authors of (van Leeuwen et al., 2017) suggested six areas for energy transition.

1. transition of energy source – move away from fossil fuels towards renewable sources
2. transition of energy consumption – other technology which use other forms of energy, i.e. electrification of heating demand
3. social transition – increased citizen awareness and involvement, e.g. development of local energy service companies
4. agricultural transition – balancing land use for food and biomass production,
5. tax transition – shifting energy taxes in favour of renewable energy consumption and investments
6. macro-economic trade transition – changing dependence of industrial activities and jobs from fossil fuel trade towards renewable energy trade

To the above six points, I would add the market support mechanisms for the renewable technologies. However, to realise this transition, the technological aspects of the existing electricity network or the grid need to be briefly defined first. The term "grid" is commonly used to describe an electricity system supporting four operations; electricity generation, electricity transmission, electricity distribution, and electricity control (Strielkowski, 2017). With the inclusion of renewable energy technologies in the grid, the traditional grids are evolving to "smart grids". The different aspects of the old grids and the changes that are occurring in these aspects are discussed in the section below.

1.4.1 Electricity Network as a Socio-technical Complex

As previously mentioned, energy systems are complex socio-technical systems; the grid is one example of that, as shown in Figure 1-2.

In this section, the electricity grid is presented as a socio-technical complex divided into the five LESTS domains.

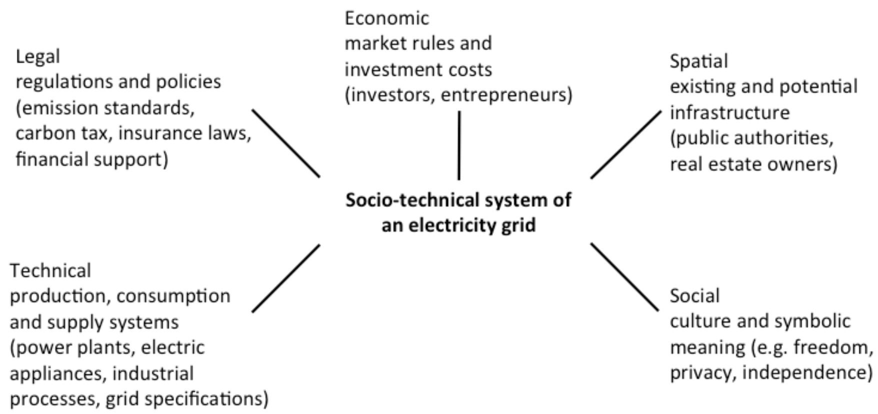


Figure 1-2: Socio-technical system for the existing electricity grid, inspired by (D. I. F. W. Geels, 2005)

The aspects that are discussed below are by no means exhaustive. The following section is meant to show the variety of challenges that are faced by our global society in its move to low carbon energy.

Legal

The legal aspect of the socio-technical system includes, not exclusively, the policies that influence the preference for the source of power, the profits for different actors, designing markets and their rules, supporting infrastructure, risks and liability distribution between different actors, and the prices for the customers. Considering the European commitment to increase consumption from renewables and at least 40% cuts in greenhouse gas emissions (from 1990 levels), the move towards renewable energy is being realised by carbon taxation and incentives for renewables.

Renewable energy policy is inevitable in the move towards a low carbon future. Authors of (Shum, 2017) discussed the different financial incentives to invigorate the renewable energy fed into the grid. These financial schemes can vary from taxing the carbon emitters and subsiding the feed-in volumes from renewable sources, to financially supporting the technology development and knowledge diffusion in the society to indirectly create positive feedback loops for renewable energy. The latter set of mechanisms includes easier access to the grid for the greener energy producers, as well as favourable schemes to protect the green energy providers on the market in case of deviations from predicted volume. The predicted volume of production from the energy providers (and predicted volume of consumption by consumers) is called a portfolio.

At the level of the actors, these legal aspects take the form of legal obligations contracts. Authors of (Gatzert & Kosub, 2016) studied different risks and their current management specific to the on shore and off shore wind park projects in Europe. According to their observation, current insurance products comprehensively cover the technical risks of wind parks are. However, the risks for investors of offshore wind farms (especially construction and operation) are not well covered. Other challenges include the complexity of contracts due to a large number of parties involved in these projects and their liability in cases of loss. These losses, due to vulnerability to weather conditions, can be caused by imbalance in the portfolio of the providers. The biggest risk for the investors of wind farms remains to be policy and regulatory risk.

Economic

An important aspect of the socio-technical complex is the role of entrepreneurs and investors of the technology. The expected result of the policies that support the producers and providers of green energy with the safety to experiment with innovative technologies is to passively affect the economic cycles of the market in favour of the renewable energy technologies. In 2018, 26.7 billion euros were spent alone on wind energy projects, of which 16.4 billion was spent solely on onshore wind energy (windeurope.org, 2019). Different market integration schemes and support mechanisms have been developed for increasing the injection of Electricity from renewable energy sources in the grid and to restrict the costs induced by the variability and limited predictability of renewable energy generation. In liberalised power markets, these costs occur as imbalance costs, which is defined as a penalty for deviating from the submitted production and consumption plan (De Vos, 2015). In extreme cases the unpredictable renewable energy that are protected from the market effects by different financial incentives, like the tradable green certificates and the feed-in tariffs contribute to causing a negative market price (Brandstätt et al., 2011; De Vos, 2015; Fanone et al., 2013).

Investment grants, renewable energy quotas, feed-in-tariffs, green certificates, etc. also generate incentives to invest, which indirectly increase competition and improve technology leading to cost reductions and volume growth (P. D. Lund, 2009). Eventually, the renewable energy push the expensive systems like nuclear and gas fired power plants out of the market and lower the market price due to their negligible marginal costs. However, this increases price volatility on the market. Extremely high prices are caused when demand peaks as compared to the supply, this could be an effect of expensive and reliable but rather inflexible power production technologies, such as the nuclear and fossil fuelled power plants and low wind power due to weather conditions (De Vos, 2015).

The financial incentives for the renewable energy producers are designed in a way to shift the additional cost to all ratepayers connected to the grid (commons), hence, as more customers shift to responding to RE supply the less amount is paid by the commons (Shum, 2017). This impacts the system in a way that the actions of renewable energy providers and flexible consumers benefit the whole system by driving the price of electricity low. All consumers benefit from lower electricity prices and not just the providers of demand flexibility, the benefits of demand response can be considered to be truly societal in nature (Baker, 2016; Shum, 2017).

Spatial

Socio-spatial aspects of energy transition have received little attention from academia. Recently these aspects are emerged on the research agenda. Authors of (Gailing et al., 2019) studied the energy transition in Germany under the TPSN (Territory, Place, Space and Network) framework. Their main findings show that conflicts that arise between the renewable energy farms and local communities mostly relate to changing the identity of the region. Communities may want to preserve the ‘green’ or ‘pristine’ image of the region and may oppose large-scale energy production systems. They also found that identifying an area as ‘bio energy region’ or a ‘green city’ creates an identity of the space and legitimises renewable energy development.

Spatial aspects, just like socio-economic and judicial aspects in any location are unique to that region. For example, in the case of Japan, the inclusion of wind power in the grid has faced a technical problem because optimum location for the wind farms in an area where the grid lines were not installed for high voltage transmission (Moe, 2012). Hence, the country has favoured solar power over wind power. This provides an example of how spatial aspects can result in one energy technology being favoured over others based on purely spatial reasons.

On the actor level, spatial aspects of renewable energy production can result in directly affecting the real estate prices and opposition from the community, in case of a negative effect, or vice versa.

Technical

Old electricity grids were set up for the one-directional flow, from the producers to the consumers. The supply networks, control, management and communication systems that evolved to support the grid fulfilled the needs of that time. However, the production systems are changing to renewable and hence unpredictable ones, the supply network needs to adapt to the bi-directional flow of energy, the consumers need to be supplied with technologies that support consumer response for grid flexibility, etc. With the aim to move towards a low carbon future, nations and international coalitions are attentive to the challenge of this shift.

In the period of 2020-2025 a 5,000 MW of nuclear energy is scheduled to be phased-out when seven nuclear reactors will be shut down in Belgium (*Belgium Maintains Nuclear Phase-out Policy - World Nuclear News*, 2018). If the phase-out is carried through, it is speculated that Belgium's carbon footprint will deteriorate as the firm capacity will need to be replaced by fossil-based power plants. However, if this capacity is replaced with renewable energy technologies, the effects on the grid balancing and market prices will be significant. The technological issues of a smart grid development projects in Europe are discussed in detail in the publication of (Colak et al., 2016), who mentioned the critical challenges in smart grids in terms of information and communication technologies, sensing, measurement, control and automation technologies, power electronics and energy storage technologies.

Traditionally, established technologies of power production, e.g., coal-fired, gas-fired or nuclear power plants were used to provide the needed backup capacity (ancillary services) to the grid, maintaining a safe operation. However, since renewables have successfully entered the electricity market, the need for system security has been increased. It is estimated that for every 8 MW of wind power installed, a 1 MW of peaking plant is required (*Peak Gen Power*, n.d.), whereas, it is also estimated that most of the peaking gas units today operate at below 20% utilisation rates (windeurope.org, 2016). Use of demand side response as a grid balancing strategy is a recent phenomenon (Kim & Shcherbakova, 2011) but it shows promising potential, especially when coupled with increased wind power injection (Paulus & Borggrefe, 2011). Demand side response is a set of measures that uses loads, local generation and storage to support network operations and also to enhance the quality of power supply (Qadrdan et al., 2017). Demand side response has been proven to reduce the needed conventional generation capacity, to maximise the low carbon generation, to contribute to short-term system balancing and to defer the network reinforcements (National Grid Electricity System Operator & Sustainability First, 2018). The energy intensive industries have been assessed for their potential of DSR in the works of (Paulus & Borggrefe, 2011) and (Ashok & Banerjee, 2000) and high energy intensity is the main lever for demand flexibility to be an attractive option for industrial processes.

A publication of the author on this topic studies the effect of limited generational flexibility of the wind farms that receive a feed-in tariff for each unit of renewable power they inject in the grid, against the reserves provided by the industries as flexible demand (Maqbool, Baetens, et al., 2019).

Social

A grid that has remained unchanged for nearly a century is facing tremendous resistance in the social domain to transition to a smart grid. Smart appliances, heating and cooling systems for households prove to be a challenging technology to diffuse into the everyday lifestyle of the society. Authors of (Larsen et al., 2019) refer to numerous studies that show consumers prefer comfort and control over the reduced bills that smart heating systems provide. Especially when consumption flexibility is used for grid balancing, it is usually studied as part of a centrally controlled system, which takes away much of the control from the user (Larsen et al., 2019).

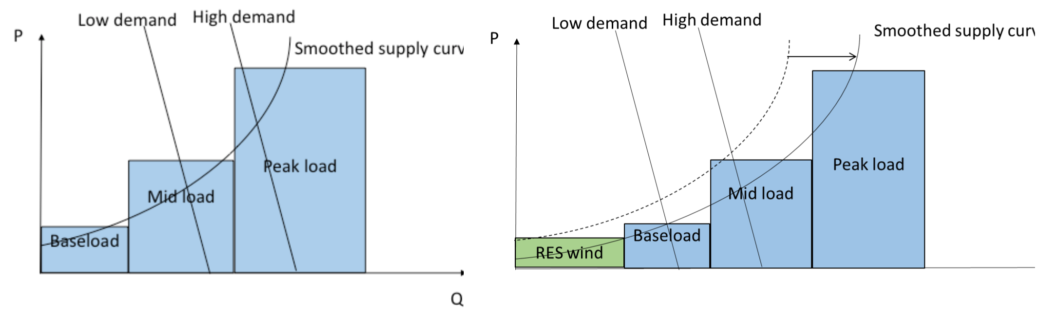
Concerns over data security and privacy have also arisen on the agenda since the introduction of smart grid idea. Developments in the field of information and technology are crucial to bring about the transition from a traditional grid to a smart one (Colak et al., 2016). Often the developers of smart technologies also naively consider all the consumers to be technologically savvy (the Resource Man) and fall short of considering the requirements of different demographic groups (Strengers, 2013).

Consumer behaviour is another challenging domain of the social aspect of system transition. Certain feedback loops caused by consumer behaviour can offset the positive effects of the system change. Authors of (Brännlund et al., 2007) calculated the carbon dioxide emissions that were off-set by the increased energy efficiency. Their results showed that improved energy efficiency does not reduce carbon emissions because the overall consumption increased. This negative effect is termed as the rebound effect.

1.4.2 Electricity Markets and Grid Balancing

Balancing the potential supply and demand of electricity at any given time ensures a reliable supply of electricity. Transmission System Operators (TSO) are entrusted to carry out the necessary security checks and real-time operations of ensuring a smooth supply of electricity to the consumers (De Vos, 2015). To make this possible, the majority of electricity trade is conducted up to one day before delivery. Based on the time dimension, energy trade is divided into different markets in Europe.

This thesis focuses on the Day Ahead Market (day ahead market) and Imbalance Market (imbalance market). The design and rules that are discussed below for both these markets are based on the principles of electricity markets in Belgium (*Balancing Mechanism - Elia*, n.d.; Elia, 2012). To ensure more transparent market pricing system, in both markets buyers and sellers trade electricity following an energy exchange. For the day ahead market, the intersection of scheduled production and consumption profiles provide the market prices for each hour of the next day, as shown in Figure 1-3 (a). The renewable energy technologies have the lowest marginal costs as compared to the other technologies and hence are the first ones in the order. The effect of RES pushes the supply curve to the right and this is shown in graph (b) of Figure 1-3.



(a) (b)

Figure 1-3: Theoretical merit order without (a) and with renewable energy from wind (b) (based on (De Vos, 2015)) (P=price of electricity, Q=installed capacity shown as ratio to the average system demand)

The potential forecasts for demand can be faulty and may still cause imbalances in real time, coupled with increased unpredictability due to increased injection of wind power results in higher demand for reserves (Misra et al., 2015). Imbalance market or balancing market represents the market where trade of deviations from the scheduled market positions is dealt with (North et al., n.d.). A real-time balancing market is particularly useful for renewable energy as they can provide higher forecast reliability closer to real time (Brandstätt et al., 2011). Due to the very fast response times required to balance this market and the connected security issues, this market is coordinated by the TSO (Vasirani et al., 2013). Conventionally, TSOs contract minimum reserve from firm capacity, or power plants with technology that can be easily ramped up and down to balance the grid, however, now regardless of the source technology, reserves are being contracted by the TSOs. Usually these contracts are of long-term nature but in some cases, like Belgium, even short term additional capacity can be offered one day before real-time (De Vos, 2015). Together these reserves form the activation price ladder that is shown in Figure 1-4, on the next page. The terminology, cheap, mid-priced, and expensive refers to how much the TSO will have to pay for the reserves in case of grid imbalance.

In order to ensure system security, TSOs procure balancing services from balancing services provider. A part of the balance obligation is allotted to market participants or their chosen representatives – known as balancing responsible parties. These balancing responsible parties ensure that their portfolios are balanced. These parties can commit to respond to the requests from TSO to change their portfolio. These responses can be carried out by altering the portfolio in both directions, known as upward or downward reserve activation.

Upward reserve activation is required when the system faces a power shortage (negative imbalance) and this results in a positive marginal price on the reserve market. This means a price is paid from the TSO to the agent, which may include the costs of fuel that is required to increase the output of a power plant, the cost of battery maintenance, or the loss of production from the industries. Downward reserve activation is required when the system faces power excess (positive imbalance), which may result in negative prices. Following the imbalance market pricing mechanism in Belgium, a one-price settlement mechanism for the imbalance market is set. This represents the settlement side of the reserve market, where a price is quoted every quarter of an hour, which represents the marginal activation cost of the reserves shown in the bidding ladder in Figure 1-4, on the next page.

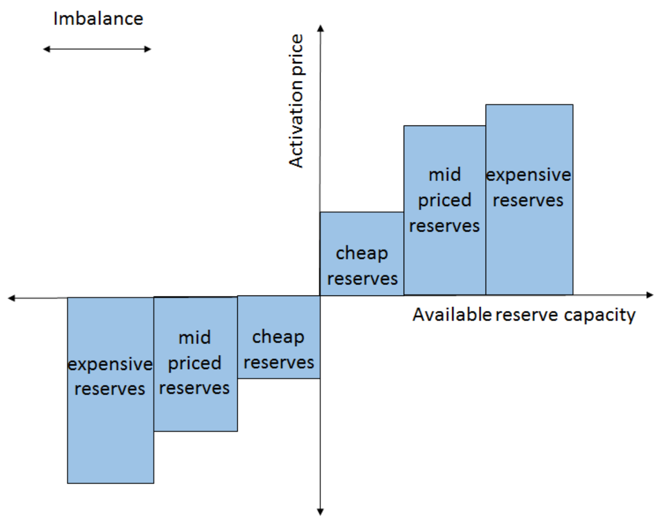


Figure 1-4: Bid ladder for activating reserves. Positive when available reserve capacity is used for upward activation and negative when downward activation is required (based on (De Vos, 2015)).

1.4.3 Modelling Electricity Markets

Electricity grid and markets are composed of multiple actors, who are engaged in consumption/production of electricity that fulfil their own needs and businesses, and their interactions via the market and the electricity grid results in impacting the consumption/production pattern of each other. Agent-based modelling allows to mimic the behaviour of human beings and simulate production, consumption and bidding process, in which participants are modelled as adaptive agents with different strategies (Li & Shi, 2012). "The aim of agent-based modelling [or simulation] is to search for explanatory insight into the collective behaviour of agents obeying simple rules, […], rather than in designing agents or solving specific practical or engineering problems"(Niazi & Hussain, 2011). Agent-Based Models (models) have been used to model the diffusion of energy efficient technologies through the society by the interaction of different agents (Schramm et al., 2010; Sopha et al., 2013). models are used to explore possible states of a system to understand plausible futures, trends, tendencies, and behaviours that can occur under specific circumstances (Koen H. Van Dam et al., 2012).

Previous work on the use of models for electricity grids, markets and the injection of renewables have focused on the effect of prosumption and peer to peer supply and its effect on the grid management (Bellekom et al., 2016) and grid design strategies (Fichera et al., 2018). Models have also been used to predict price of energy trading in smart grids by the use of incomplete information by different agents to optimise their own utility (Misra et al., 2015). Likewise they have been employed as an e-laboratory to test different regulatory interventions before implementation (North et al., n.d.). Furthering the investigation on the profit renewable energy producers, model has been used to study the optimum conditions for the wind power producers participating in a deregulated market with the inclusion of learning algorithms to optimise the bidding process (Li & Shi, 2012). Similarly, the technique has been employed to investigate the effect of storage possibilities in the form of electric vehicles on the profit of wind farms that engage in the electricity markets (Vasirani et al., 2013).

Electrical flexibility, defined as 'the extent to which a power system can modify electricity production or consumption in response to variability, expected or otherwise' (International Energy Agency & Organisation for Economic Co-operation and Development, 2011), has been widely accepted as an effective strategy to overcome the friction faced by technologies based on renewable energy sources (RES). Lund et al. (2015) categorise flexibility into, flexible production, storage, flexible consumption and interconnection (Peter D. Lund et al., 2015). As the definition of flexibility shows, it involves both producers and consumers to cooperate in order for the electric grid to remain in balance to avoid black outs and extreme electricity prices. In this way, flexibility is a symbiotic relationship, where the benefit of cooperating is higher than maximising own profit. However, quantification of costs and benefits of each actor is necessary to devise effective incentives.

1.4.4 Case study: Flexibility and a low-carbon grid

A case study of a hypothetical electricity grid is included in this thesis to provide a multi-lens perspective to tackling the pressing challenge of sustainable energy transition. In the recent decades, technical advancements and subsidies for renewable electricity production technologies have enabled their successful diffusion in the existing energy regime. However, new questions have risen on the horizon of public policy. Questions that trigger one to think if feed-in tariffs encourage wind farm owners to operate less efficiently. Feed-in tariffs have proven to be superior for wind power promotion in countries like Denmark, Germany and Spain (Menanteau et al., 2003; Meyer, 2003) but such a system does not force the renewable energy producers to operate cost efficiently (Verhaegen et al., 2009). Although the subsidies for renewable energy producers are slowly being phased out, the question is if the subsidies are negatively affecting the unharnessed potential of demand side response as means to accommodate renewable energy in the existing electricity network.

Large energy consumers, especially industries are also curious about the economic benefits of consumption flexibility and the impact of increased renewable energy being injected into the grids. Likewise, with more households installing PV panels for self-consumption, public authorities want to estimate how much of the over-production from the households can be consumed by the system so that the burden on other power production systems is reduced.

The case study includes an agent-based model of a hypothetical standalone electricity network to identify how industrial flexibility, feed-in tariffs and the installed capacity of wind power, calculated in percentage of total system demand, affect the electricity consumption from renewables. It includes the mechanism of electricity pricing on the Day Ahead Market and the Imbalance Market. The extra production volumes of electricity from renewable sources and the flexibility of electrical consumption of industries are provided as reserves on the imbalance market. 6500 simulations were run using the agent-based model to gather data that were then fit in linear regression models. This helped to quantify the effect of industries' electrical flexibility, feed-in tariffs and installed capacity of wind power on the consumption from renewable energy and market prices.

There are three main methodologies for modelling electricity grids in transition to a renewable energy system, identified by (Ringkjøb et al., 2018), namely – the optimisation models, the simulation models, and the equilibrium models. The optimisation models provide least expensive or most environment friendly techno-economic solutions. The equilibrium models provide insights into the electricity markets as part of a larger economy and may answer to evaluate the impact of various policies on the economy as a whole. In this case study, the agent-based simulation was used due to its ability to model different strategies and behaviours of the agents. This is the defining characteristic of complex systems (as explained earlier). Agent-based simulations help policy makers to explore possible system responses to any intervention.

The agent-based models are also able to include technical details of different agents to a minute detail, which would allow the industries to be modelled with their different electricity intensities. This was not a parameter of interest in this case study but is an important one that can help define technical details of flexible consumption of any industry.

1.5 RESEARCH AIM, OBJECTIVE, AND QUESTIONS

The overall aim of this thesis is to explore the potential of industries to cooperate in a sustained fashion among each other and with other (meso-level and micro-level) actors and move towards an energy and resource efficient system. This aim defines the overarching research question that is confronted in this thesis:

How can the cross-boundary industrial interactions help the move towards resource-efficient and low-carbon future?

This explorative question is conceptualised by identifying industrial networks and energy systems as complex and dynamic systems. It inquires the sequence of events that lead to certain conditions that reinforce the cooperative activities to foster and strengthen over time. First, the conceptual objective is to understand the preconditions for industry to engage in industrial symbiosis and facilitate the identification of opportunities for reduced material and energy waste. Second, the analytical objective is to quantify the effect of electrical flexibility of industries on the successful injection of renewable energy in the grid. The following sub-questions help to reach a concluding answer to the research question.

1. What are the dynamics in the different industrial clusters included in the case study that define their industrial symbiosis?
2. How can the industries be facilitated to identify symbiotic opportunities?
3. How does the industrial electrical flexibility affect the transition to a low-carbon electricity grid?

1.6 THESIS OUTLINE

In light of the science supporting anthropogenic reasons for climate change and degradation of biophysical environment, it is only rational that every little change in the current way of operation is considered important. Likewise, disruptive changes cannot be excluded any longer given the harmful impacts that climate change will have on the human population (IPCC, 2014, pp. 15–16). This thesis deals with both views; one focuses on exploring opportunities to reduce primary resource use and improve efficiency in the industrial processes, while the other address the effect of electrical flexibility of industries on a grid that transitions to a 100% renewable energy.

The rest of the dissertation is divided into six chapters and their contents are briefly explained in Table 1-2 on the next page,.

Table 1-2: Thesis outline

Chapter	Contents
2. Methodology-I	- Methodology for studying the dynamics in industrial clusters and propose industrial symbiosis opportunities
3. LESTS assessment	- Defining the industrial symbiosis dynamics in the five industrial clusters according to LESTS - Identification of industrial symbiosis opportunities in the five industrial clusters
4. SWOT analyses	- SWOT analysis of the five industrial clusters - SWOT analysis of the most promising industrial symbiosis opportunities
5. Methodology-II	- Methodology for modelling the electricity grid as an agent-based model
6. Flexibility and a low-carbon grid	- Results of the simulations using the agent-based model - Quantified effect of industrial flexibility on the injection of renewable energy in the grid - Comparison of industrial flexibility against feed-in tariffs for producers and installed capacity of wind energy in their role to increase injection of renewable energy in the grid
7. Discussion and Conclusion	- Conclusion on the case study of industrial symbiosis networks - Conclusion on the role of industrial flexibility in the move towards a low-carbon grid - Conclusion on the role of industries in the transition to a resource-efficient and low-carbon future

CHAPTER 2. METHODOLOGY – PART I

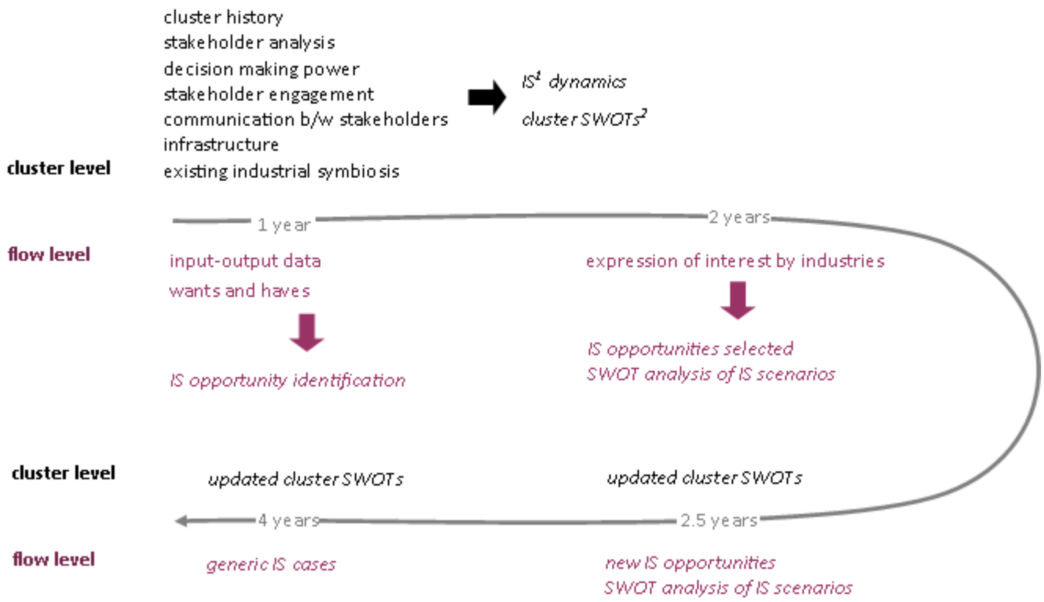
This chapter provides a method to describe the dynamics in the industrial clusters included in the case study and identification and selection process of industrial symbioses. Since the bulk of the research was conducted as part of the EPOS project for the fulfilment of the project deliverables. Hence, the method for identifying and assessing industrial symbiosis that is described in this chapter is adapted to the EPOS project objectives, the kind, and the availability of data.

Industrial symbioses involve all processes that connect flows of secondary materials and/or share services/utilities between the participating industries and the municipalities near them. The main objective of the industrial symbioses case study was to enable cross-sectoral symbiosis by providing solutions to overcome barriers, especially the lack of commitment to sustainable development, the lack of information sharing, the lack of co-operation and trust, the lack of awareness from communities and the economic infeasibility. To ensure a continued engagement of the industries and to cultivate the seeds of cooperation among them it was planned to have regular updates on the process of industrial symbiosis identification and assessment.

The case study ran for a period of four years and the data collection and analyses carried out during this time is shown in Figure **2-1**. The methodology covers two levels of analysis. One, at cluster level, data were collected for assessing the dynamics in the clusters where the industries were located. Two, at flow level, information about the physical flows and management services was gathered that could help identify potential industrial symbioses between the participating industries in their respective clusters. These two levels and the outcomes of the data assessment are shown in Figure 2-1 on the next page.

During the first year, the focus of the study was an understanding of the industrial processes and to identify the most pressing issues that could be resolved collectively by the industries. This helped to focus the attention of further work on key areas by identifying industrial symbioses in every cluster. A cluster is defined as two or more industrial sites that are collocated and that have joined the case study with the aim of enhancing economic gains, environmental quality and social responsibility for the business as well as the local community through industrial symbiosis.

In parallel, the industries carried out material and energy inventory of their sites to support the development of generic models that could help overcome the problem of data sharing among them. These generic models are termed sector blueprints (Cervo et al., 2020). This also helped to identify key flows that could become a reason to engage in symbiosis. During the second year, the already identified opportunities were further investigated for their implementation potential. These opportunities were ranked by the industries based on their relevance and interest. During the next year, these opportunities were translated into business cases. New symbiosis cases were also identified during this time and added to the list of opportunities.



IS[1] – Industrial Symbiosis, SWOTs[2] – Strengths, Weaknesses, Threats, and Opportunities. The normal text shows the inputs while italic text shows outputs

Figure 2-1: Timeline of the cluster and industrial symbiosis assessment methodology during the course of four years

In the final year of the project, the symbiosis opportunities were translated into generic cases to disseminate the results to general public, without sacrificing the confidential information. A last evaluation of the collaborative activities on each cluster was also carried out to assess the progress made on each cluster during the four years of the case study.

All this work is systematically combined with the other tools and methods used in the research project EPOS. The combination formulates the EPOS methodology, which is considered as an industrial symbiosis accelerator enabling a fast identification of relevant industrial symbiosis opportunities and their analysis, and that could contribute to the broader dissemination of the industrial symbiosis concept. The methodology is introduced below with emphasis on the methodology of the case study.

2.1 CASE STUDY I – METHODOLOGY

The EPOS methodology was developed by the mutual efforts of the partners involved in the project. It takes an approach that oscillates between quantitative and qualitative assessment. Aptly described by Nikolic, defining the materials to be exchanged answers to *what* questions, while, working out the process to realise [material and information] exchanges answers to the *how* questions (Nikolić, 2015), EPOS methodology answers to both *what* and *how* questions.

The EPOS methodology adopts a funnel approach in terms of scope and is organised in seven interconnected steps (Figure 2-2). Step 0 through step 2 is based on the work of (Maqbool et al., 2017) and the steps from step 3 through step 7 are based on the work of Cervo & Ogé et al. (2019), while the work of (Cervo et al., 2020) supplements the feasibility study with further analysis.

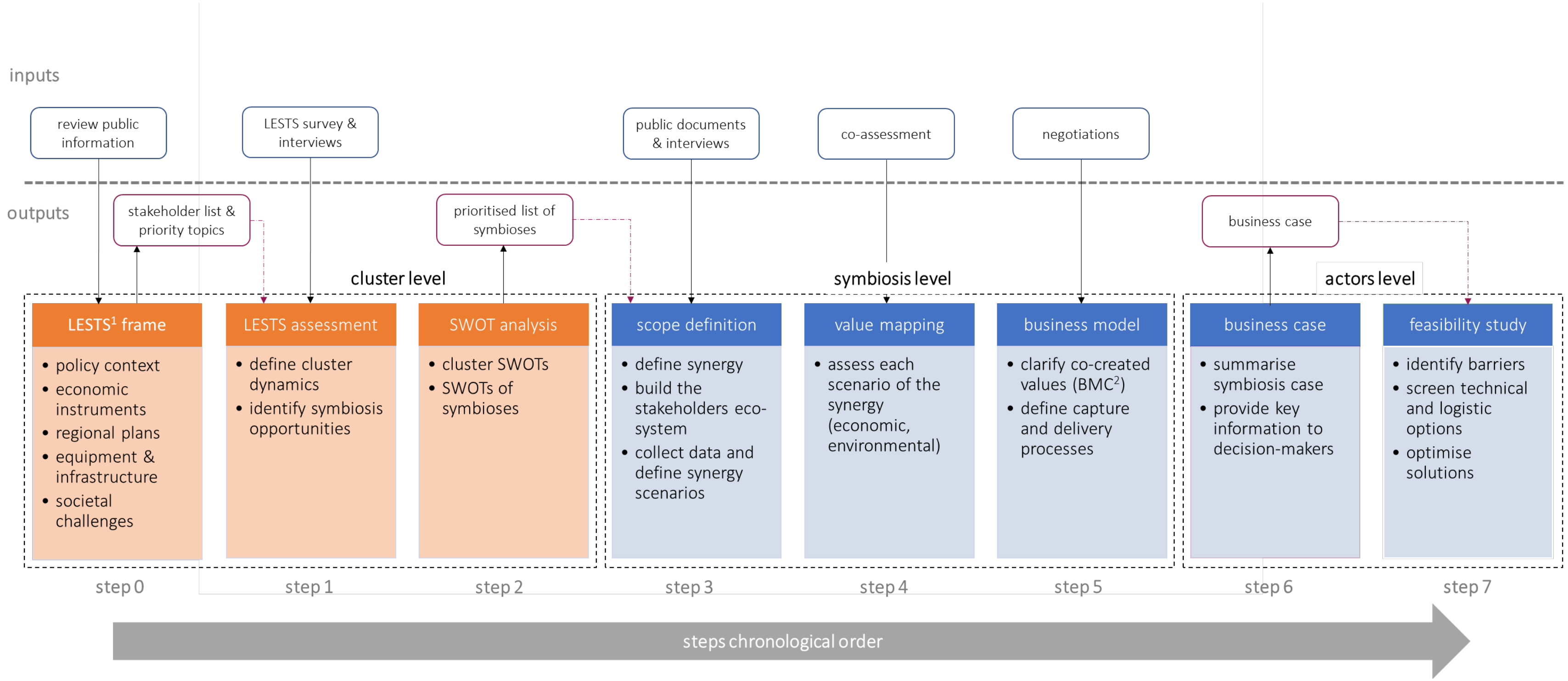
The analysis under the EPOS methodology takes place at three levels, as shown in Figure 2-2. At the *cluster level*, the steps enable the identification of industrial symbiosis opportunities between the participating actors and the examination of the background information that is of importance for the rest of the analysis. At the *symbiosis level*, the scope is reduced to the analysis of a single symbiosis that emerges from the list of previously identified industrial symbiosis opportunities. At the *actors' level*, the methodology provides decision makers with a specific business case that aims at triggering the interest of the decision makers. The last step (feasibility study) guides the firms that have decided to proceed with the symbiosis, explores the technical feasibility of the exchange, and can even help in improving the organisational aspects of the symbiosis.

The scope of the case study included in this thesis is limited to the step 0 through 2, which is related to the cluster level analysis, ending with a prioritised list of industrial symbioses and their SWOTs. The steps from step 3 through step 7 form the part of research work of colleagues who were involved in the EPOS project. These steps are not further described in this thesis.

The methodology for the case study distinctly answers the need to bring a holistic and a systemic overview when dealing with industrial symbiosis. As identified by Jacobson and Anderberg, mass flow analysis often shows a much larger potential than the actual (much smaller) symbiotic activity, which point to other factors than physical and economic that influence the symbiosis (Jacobsen & Anderberg, 2004). These factors relate to the complex combinations based on technological, institutional, organisational, economic and mental conditions, which form the dynamic behind an industrial symbiosis activity. The energy and cluster management group at Ghent University, that the author is part of, developed an assessment method that takes into account this complex combination of factors at play in any industrial symbiosis. This is the method that helped to frame the first step of the methodology and is described below.

LESTS + SWOT analysis

LESTS is an abbreviation of Legal Economic Spatial Technical [and] Social. The LESTS book series (2005) was written to assess the appreciation of existing resources at a business park and provide a set of guidelines for better park management (Van Eetvelde, Delange, et al., 2005). The original LESTS series were published in Flemish and consisted of four books: Legal, Economic, Spatial, and Technical. Later LESTS was used to aid the data collection process for a European and local project, POL 001/07, and Windkracht13 (2013-2014), respectively.



LESTS[1] – Legal Economic Spatial Technical Social, BMC[2] – Business Model Canvas.

Figure 2-2. The methodology for the case study as part of the EPOS method (adapted from (Stéphane Ogé et al., 2019))

The **legal framework** of industrial collaboration should be defined. Experience has taught that partnership initiatives between adjacent companies in an industrial zone, although having a significant positive overall effect, often fail. This is usually because there is no legal basis giving the companies certainty and clarity about their financial input, deployment of people and resources, and the allocation of tasks, decision power and responsibilities that lead to the practical implementation of the intended partnership (Van Eetvelde, De Zutter, et al., 2005).

The **economic added value** of symbiotic deals should be calculated. Companies will only voluntarily join in symbiosis if they can expect a profitable result, in other words, potential win-win situations. Examples are direct gains in the short term, a better competitive position in the medium term and a durable relationship with the stakeholders, including the government, in the longer term (Van Eetvelde, Verstraeten, et al., 2005).

The **spatial preconditions** of potential clustering should be assessed. In its most practical form site management is translated as an efficient utilisation of the available space but at a supralocal level, spatial design can also boost sustainable siting in a region. In both cases, attention should be drawn to the vitality, liveability and quality of the district, e.g. via alternating built-up parts and green zones, supply chain management, sustainable mobility, etc. (Van Eetvelde, Allaert, et al., 2005).

The **technical feasibility** of cluster activities should be realistic. The techn[olog]ical underpinning of a cluster concept is considered to be the assessment criterion par excellence for participation in a joint project (Van Eetvelde, 2005).

Since acceptance and commitment are indispensable, within the company, onsite, in the (cross-sector) cluster or the surrounding community, even at (regional) governmental level and in the value chain. Stakeholders' views are crucial to get things done, to start cluster actions and contribute to a more **sustainable society**.

Other authors have used similar categorisation for studying the effects of activities under green economy (Pitkänen et al., 2016), for grouping the barriers to industrial symbiosis (Golev et al., 2015), for defining sustainability framework in industries (Labuschagne et al., 2005), as the factors that influence the development and operational characteristics of industrial symbiosis networks (Mirata, 2004), and for assessing the macro (external) forces affecting an organisation (PEST or PESTLE analysis) (Newton, 2014).

PESTLE (Political, Economic, Social, Technological, Environment) analysis helps in mapping the external factors that influence an organisation and helps in designing a strategy. Often PESTLE analysis is coupled with SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis, which finds its roots in strategic decision-making for organisations. SWOT analysis combines the two factors that a person, business, organisation, plan, etc., may face. The SWOT analysis has two dimensions:

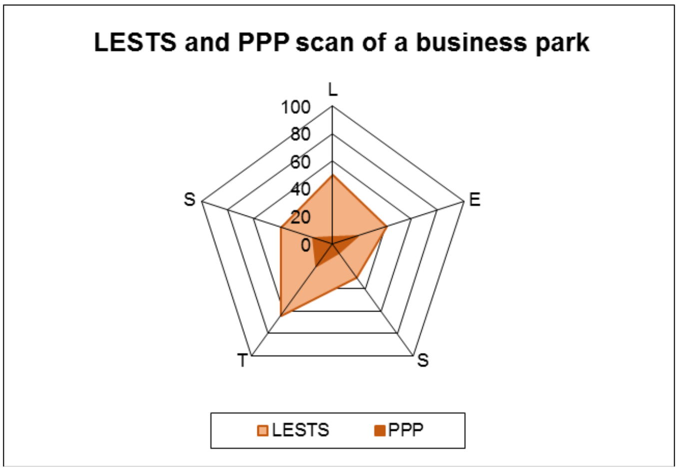
- *Internal to the organisation* – Strengths and Weaknesses
- *External to the organisation* – Opportunities and Threats

The LEST(S) book series was already written in 2005 and targeted for the park managers, who could use the LESTS and SWOT analysis to decide on their business strategy. The LESTS + SWOT methodology was customised for use by the ECM research group in research projects. In the SWOT analysis scoring of sustainable activities is done at the beginning and at the end of a study, which provides a representation of the effectiveness of the actions and helps to develop future scenarios for sustainable activities and innovations.

LESTS/PPP survey

The method followed in LESTS allows for collection of data on the five LESTS aspects of a business park with the help of a survey that is developed from a pool of predefined set of questions. These questions help to collect data on park management and site organisation, and material and energy exchange. Each question has one or more LESTS dimensions. For example, a question – *Is there a day care facility available at the business park?* The answer to this question allows assessing the availability of facilities that answer the social responsibility of the businesses in the park. The answers are ranked on a Likert scale, ranging from strongly disagree (0) to strongly agree (5). The weighted average of the answers provides the score for each of the LESTS aspects.

The same questions which help to collect LESTS data provide the performance of a business park on People, Planet, and Profit (PPP) criteria (Van Eetvelde et al., 2007). The results are plotted on a pentagon that provides both sets of results, as shown in Figure 2-3. The reason to divide the results in two sets is embedded in the theory of eco-industrial parks. Business parks or industrial agglomerates can engage in a number of cooperative activities and these define the outer LESTS pentagon. However, the evolution of an industrial park to an eco-industrial park involves a sustainable cooperation and a consideration of the PPP aspects (Van Eetvelde, 2017; Van Eetvelde et al., 2007).



LESTS – Legal, Economic, Spatial, Technical, and Social; PPP – People, Planet, Profit

Figure 2-3: Sustainability scan of a business park

Since the original LESTS/PPP survey was developed for the business clusters and focused on the mapping of collaborative activities, it had to be adapted to the objectives of the case study included in this thesis. This adapted methodology is explained below.

2.1.1 STEP 0 – LESTS Frame

Established practice of studying industrial symbiosis points to three perspectives; characterisation of the factors under which industrial symbioses form, the exchange relationships that sustain the development of industrial symbiosis complexes, and the benefits that accrue to the industries that participate in them (Y. Zhang et al., 2015). The LESTS frame helps to study the first perspective of the three.

This step of the methodology is to understand the industries that wish to engage in industrial symbiosis, to gather the information about most pressing issues that could be resolved by a cooperative approach and the local context that these industries operate in. The LESTS frame helps to formulate the data collection plan and prepare the questionnaires for data collection.

When considering the *policy context* that the industries operate in, the relevance of circular economy, low carbon economy, and Brexit (for UK partners) was taken into account. For the respective local context, the *economic incentives* to engage in symbiosis were considered to focus on the low-hanging fruits. The plans of regional development helped to understand any *infrastructure* changes. An understanding of the industrial processes of the partners defined the availability of *equipment and utility networks* that could support symbiotic activities. Great care was devised to enhance the existing stakeholder networks by new symbiosis and answer any *societal challenges*, such as job security and creation, as well as corporate responsibility.

2.1.1.1 Data collection

Extensive data were collected with the help of LESTS inspired surveys and interviews. For some industry partners within the cluster, distance to the closest industry predefined the feasibility of a limited symbiosis. For these partners, a modified survey and interview was carried out, which included fewer number of questions and focused on physical flows and not the combined management of utilities or shared services, keeping in view the distance between the industrial sites.

The LESTS survey aimed to collect following information.

Information about cluster dynamics:

1. The company and the respective cluster;
2. Cluster management and consultation at cluster level, and;
3. Stakeholder analysis, decision-making power, stakeholder engagement, communication between stakeholders.
4. Contractual cooperative activities with neighbouring companies;
5. Nature and length (time) of these contracts, and;
6. Possibility to alter these contracts.

Information about flows:

1. By-products, waste, energy, emissions, water profiles of the industries;
2. Equipment, supply chain, packaging requirements of the industries, and;
3. Infrastructure availability.

The LESTS surveys were filled in by the PhD students working for the industries for the EPOS project, with the information provided by the relevant personnel on their company site (often, site manager, energy/environmental manager). The surveys were also supplemented with semi-structured interviews to collect information about the interaction and consultation between stakeholders at the cluster level. The list of collected data and the contact person is provided in Table 2-1 on the next page. The interviews focused on gaining insight into the decision-making power of the personnel on site, stakeholder engagement at the industrial cluster level, and communication with neighbouring communities. These interviews helped to gain an overview of stakeholder perception about possibilities of engaging in industrial symbiosis. The LESTS survey is provided in annex (see Table A-1).

Table 2-1: General information about the data collection for the LESTS assessment

Cluster	**Visp**	**Dunkirk**	
Sector	SME	Steel	
Interviewees	Director of the company	Employee of the steel company and a member of Ecopal network	
Date	June 01, 2016	July 29, 2016	
Place	Skype call	Skype call	
Cluster – Lavéra			
Sector	Chemical	Steel	
Interviewees	n.a	Lead Energy Service	
Survey filled in by	PhD student on site	n.a	
Date	n.a	July 20, 2016	
Place	n.a	Skype call	
Cluster – Rudniki			
Sector	Cement	Mineral	Steel
Interviewees	n.a	n.a	n.a
Survey filled in by	Continuous Improvement Manager PhD student	PhD student on site	Lead User Energy
Date	April 27, 2016	n.a	n.a
Place	n.a	n.a	n.a
Cluster – Hull			
Sector	Chemical	Cement	Minerals
Interviewees	Process Technology Manager, since 2008	Environmental manager of the site (22 years on the site)	Head of Operations UK & Ireland – at the time of interview. Head of QSHE, Area West, Sustainability
Date	February 09, 2016	May 27, 2016	February 22, 2016
Place	Skype call	Skype call	Skype call

The LESTS analysis enabled the scanning of industrial dynamics, identification of relevant actors, and analysis of their relationships.

2.1.2 Step 1 – LESTS Assessment

The first step of the methodology leads to results for both the cluster and the flow level.

2.1.2.1 Cluster dynamics

At the cluster level, the collected data helps to define dynamics of an industrial symbiosis. In the case of an existing industrial symbiosis, the cluster is categorised as one of outcomes of the seven outcomes of industrial symbiosis dynamics proposed by Boons et al. (2017) (Boons et al., 2017).

2.1.2.2 Identify and prioritize symbiosis opportunities

At the flow level, the methodology helps to identify industrial symbioses between the different partners.

Table 2-2: scale for expressing interest in any industrial symbiosis case based on technical and organisational feasibility

Level of interest				
1	2	3	4	5
Technical suitability				
Technically, it does not make sense for the specific production system	Complex changes in the existing infrastructure are required (implying unreasonably high costs)	Technically, it makes sense for this specific production system	Infrastructure and/or other conditions are fulfilled to some extent or can be improved without major challenges	No major infrastructural challenges exist, and other conditions are fulfilled
Organisational suitability				
Not in line with the organization's goals and strategies	Organisational resources (time, budget, etc.) are not available, and/or should not be directed at this measure	Partially in line with the organisation's goals and strategies and is considered relatively important	In line with the organisation's goals and strategies. The necessary organisational resources (time, budget, etc.) are not available, but this could be changed	The measure is considered important by the organisation and the necessary organisational resources (time, budget, etc.) can be allocated to this measure

The data collection through the survey led to a longlist of potential exchanges and interactions between the companies - and even municipal communities - in the region. The selection and prioritisation of these symbiotic opportunities is done by the industries. This helps to focus the attention of further assessment on the most promising opportunities. The industries were asked to rank the identified symbioses on a scale of 1 to 5 in order of increasing interest based on two aspects: (1) technical suitability and (2) organisational suitability (see Table 2-2 on the previous page). The ranking system is inspired by the work of Feiz et al. (2015), who proposed a similar ranking system for assessing CO_2 measures in cement plants (Feiz et al., 2015).

Since more than one industry ranks the same list of opportunities, their answers are aggregated and a shorter list of opportunities is prepared. Based on EPOS experience, if a symbiosis scores above 3, it has a potential for implementation and it is selected for further investigation

2.1.3 Step 2 – SWOT Analysis

2.1.3.1 SWOT analysis of clusters

During this step, the most relevant pieces of contextual information from step 1 are used and are presented using the well-known SWOT analysis. A numeration of SWOTs of each cluster is carried out, which indicates strengths and weaknesses (internal factors) that induce opportunities or point to threats (external factors). It helps to list recommendations that suggest a way forward in achieving the goal of resource and energy efficiency within the cluster.

2.1.3.2 SWOT analysis of symbiosis opportunities

In addition, SWOT analyses of the selected opportunities is carried out in order to streamline the data collection and analysis carried out during the succeeding steps.

The case study included two district networks (Visp and Dunkirk), which involve an industrial partner providing heat to the neighbouring community. These clusters did not include a second industrial partner and hence the identification of industrial symbiosis for these clusters was not possible. The three other clusters (Rudniki, Lavéra, and Hull) included at least two industries that participated in the cluster. Identification of symbiotic activities and SWOTs of the most promising symbioses were enlisted for these clusters. Table 2-3 shows the scheme of which assessment and analysis was carried out for which cluster.

Table 2-3: Scheme of LESTS assessment and SWOT analysis of the clusters

Cluster	LESTS assessment & SWOT analysis of the cluster	SWOT analysis of existing symbiosis	Identification of symbioses	SWOT analysis of prioritised symbiosis opportunities
Visp	+	+		
Dunkirk	+	+		
Rudniki	+		+	+
Lavéra	+		+	+
Hull	+		+	+

2.1.4 Step 3 Through Step 7

As mentioned before, these steps of the EPOS methodology are proposed by colleagues of the author and formulate a part of their individual research. Here, only a brief explanation of these steps is provided.

Step 3 defines the scope of the further analysis. It narrows the focus towards the most promising symbiosis cases and the most relevant stakeholders. Step 4 defines the value mapping process and maps all the values that are created or destroyed through the process of symbiosis. Step 5 defines the business model of the symbiosis and draws from the business model scheme proposed by (Stephan Ogé et al., 2019). Step 6 goes further in defining the details of the symbiosis by elaborating on the business case. This leads to the final step where the business case is checked for its feasibility by the stakeholders. Here, barriers are identified and if the benefits of the symbiosis outweigh the cost and effort to remove the barriers, the feasibility study is completed and the stakeholders move on to negotiate the terms and conditions of the contracts.

CHAPTER 3. LESTS ASSESSMENT

This chapter is dedicated to the explanation of cluster dynamics in the industrial clusters and the preliminary list of symbiotic opportunities that was presented to the industries. At the end of the assessment of each cluster, a list of selected opportunities is provided. The assessments are based on the secondary data that were collected through online research and on the primary data that were collected with the help of surveys and interviews.

3.1 RUDNIKI (POLAND)

The Rudniki cluster lies in Mid-western part of Poland, as shown in Figure 3-1. The partnering industries include cement, steel and minerals, with cement industry in lead of the cluster. Instead of the names of the businesses, the companies are identified by the industrial sector followed by their location. Unlike the other clusters in the case study, the industrial partners in the Rudniki cluster are located much farther away from each other. The shortest distance between two industrial sites are 76 km apart.

Figure 3-1: Location of Rudniki cluster

The surveys and interviews were carried out with the purpose of an input-output matching between the different industries. Due to the distances between each industrial partner in the Rudniki cluster, no existing social ties were found between them. Still, an LESTS survey was conducted at Cement Rudniki and Minerals Jasice site, however, due to the distances between partner sites, Steel Krakow and Minerals Romanowo sites were only sent a short list of questions. These questions were directed to gain information that is most relevant for realistic collaborations despite the physical distance between partners.

3.1.1 Cluster Dynamics

3.1.1.1 Social

There were no social ties identified between the industries in Rudniki cluster. Due to the large distances between industries in Rudniki cluster, it was evident that the personnel from the industrial sites do not socialise in the same local networks and also, the local dynamics and historical developments in the region were very different for each industrial site. Following is a brief introduction of each industrial site and an historical overview of the industrial activities on each site.

Cement Rudniki – Lead site

Situated near Czestochowa, the Rudniki plant is a cement manufacturing site and provider of building materials. History of cement manufacturing in Rudniki dates back to 1897. The construction of the existing cement plant began in 1960. Throughout its history cement plant has undergone changes in its ownership structure, modernisation and different developments. Cement Rudniki plant occupies an area of 0.42 km^2 in Rudniki and employs about 200 people. Cement Rudniki is a member of the Cement Sustainability Initiative.

Minerals Jasice – Satellite site

Minerals Jasice produces different industrial grade minerals, mainly dolomite and employs 46 people. The management department of Minerals Jasice site is located in Warsaw. The plant operates a dry process and produces powders of different grain size. The plant has an own railway connection and is situated along the railway tracks. All raw materials come from minerals quarry in Romanowo. On request of Minerals company, the other satellite site at Romonowo was also included in the assessment.

Minerals Romanowo – Satellite site

The minerals Romanowo site consists of a quarry and two production plants: **Romanowo 1** lies at a distance of 1 km from the quarry, **Romanowo 2** is situated at a distance of almost 2.5 km from the quarry. Total area covered by industrial installations is approx. 1 sq. km. The plant is located close to a village and approximately 15 km away from the next city. Romanowo sells its products (fine granules, coarse granules, fine powders) to building industry, paint industry, plastic industry. A major share of the produced tonnage (ca. 30%) is sold to agricultural industry, where it is used as fertilizer.

Steel Krakow – Satellite site

The steel plant in Kraków was set-up in 1954. During the first stage of its operations it produced merely 1.5 million tonnes of steel per year. Over decades it was extended and modernised, new units like another blast furnace, sheet rolling mill for bodywork sheet production, electro-galvanising line and continuous steel casting line were constructed. The state-of-the-art hot strip mill, inaugurated in 2007, still remains the most modern facility and the largest investment of that kind in Europe within the last 20 years. About 70% of the Polish steel production capacity is installed in Krakow.

3.1.1.2 Legal

Industrial partners in Rudniki engage in collaborative activities with their respective neighbouring industries. For example, cement buys lignite fly ash from a coal power station located 60 km north of Cement Rudniki site. Cement Rudniki has indirect contact with some Silesian power stations via an intermediary company to obtain pulverised fly ash, which is used in manufacturing of certain cement types. There are some other supply contracts between smaller businesses and cement.

Minerals Jasice site also engages in different business activities with local businesses but no existing industrial symbiosis activity was reported in the LESTS survey. Minerals Romanowo site, which consists of a quarry and two production plants, uses the services of a third party for internal transport (from quarry to production lines) of raw material. By-products from the quarry are sold to external company, who uses them for road works (e.g. gravel).

Steel Krakow sells Blast Furnace Gas (BFG) and Coke Oven Gas (COG) to a neighbouring power plant where it is used for electricity production. Steel Krakow has leased plots on their site to many companies who use steel products, also electricity is provided to these companies via the grid owned by the steel company.

These activities show that the industrial partners do engage in industrial symbiosis with other companies that are not part the case study, however, since the scope of the case study is limited to the collaborations between the five industrial sectors, no further information about these symbioses was collected. The only collaboration between the partners in Rudniki cluster is between cement and steel.

3.1.1.3 Economic

In Poland, the White Certificates scheme is implemented to support the energy efficiency improvement in the industrial systems. This incentive could not be of benefit on each individual site but proposing symbiosis activities between the industry partners that could be eligible for white certificates was found infeasible due to the physical distances. The only economically beneficial activity related with substitution symbiosis can be inferred from acquisition of blast furnace slag by cement, a part of which is generated at steel Krakow.

3.1.1.4 Spatial

The partner industries in Rudniki cluster are spread over a large area, as shown in Figure 3-2. The approximate distance between each partner is more than 150 km. minerals Jasice plant (point A in the map) lies at a distance of 440 km (via train) from the other minerals plant in Romanowo (point B in the map). The train brings raw material to Jasice plant from Romanowo plant twice a week and does empty backloads. The reason that the train travels back empty lies in the required quality of Minerals's product. Level of whiteness of the quarried material is a criterion for the quality of the raw material for minerals and any contamination in colour is undesirable.

Distances between the three industries via road are provided below

- minerals Jasice to cement site = 195 km
- cement to steel Krakow = 164 km
- steel to minerals Jasice site = 165 km
- cement to minerals Romanowo site = 224 km

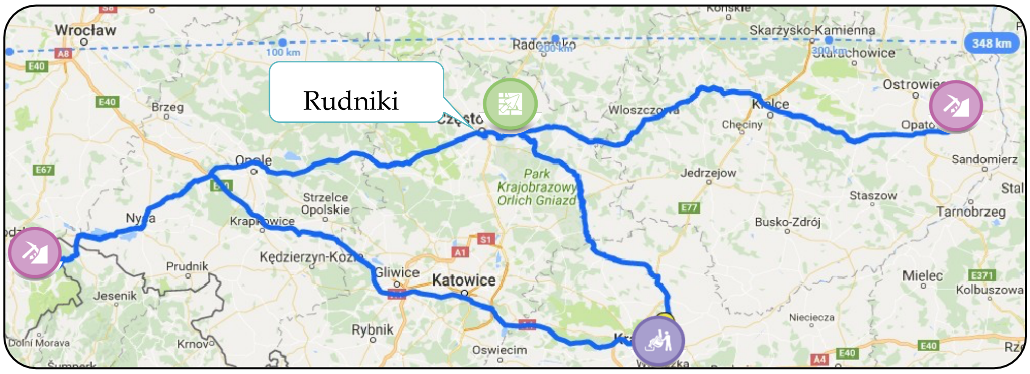


Figure 3-2: Location of industries in the Rudniki cluster

The positive aspect of the Rudniki cluster is all industries are located next to railway lines. It provides a good opportunity for them to connect and possibly engage in material exchange.

3.1.1.5 Technical

The Rudniki cluster provides a very interesting mix of industries that can benefit from each other's by-products and waste streams. The fact that a train brings raw material from minerals Romanowo to Jasice plant and travels back empty could prove an opportunity to overcome the issue of distance between the industries. The train could be used to transport material from minerals Romanowo to cement or steel and back.

3.1.2 LESTS Outcome

The only existing link between any two industries in Rudniki cluster was found between Cement Rudniki and Steel Krakow. The slag that Cement buys was bought from steel plant, however, this legal contract was not between Cement Rudniki and Steel Krakow but carried out through a third party. This shows that between the two industrial sites there were no direct links at the time of the interviews. Neither of the two partners elaborated further on the details of this business transaction. During the fourth year of the case study, the two industrial sites entered in a direct exchange of materials, but these details were not shared with the author and kept confidential.

The Rudniki cluster does not fit the criteria of an industrial cluster defined by physical proximity. However, the concept of a virtual eco-industrial park fits the Rudniki cluster despite large distances between symbiotic entities (Lowe, 1997; Y. Zhang et al., 2015). The assessment of the industrial symbiosis dynamics in the Rudniki cluster according to the characterisation of Boons et al (Boons et al., 2017) describe it as a **self-organised**, although it only contained one symbiotic activity during the case study. According to the three stages of industrial symbiosis, as defined by Chertow and Ehrenfield (2011), the Rudniki cluster shows the early stages of **sprouting** due to the one symbiotic link made between steel and cement industry.

3.1.3 Symbiosis Opportunities

The Rudniki cluster posed a challenge in identifying economically feasible industrial symbiosis opportunities between the industrial partners. Table A-2 in the *annex* provides all the possible symbiotic opportunities that were proposed to the industries. However, the physical distances proved to be an insurmountable hurdle to realise almost all of the opportunities. All industry partners in Rudniki were interested in the symbiotic activities, as is visible by the level of interest that was shown by them in Table 3-1.

Table 3-1: Shortlisted industrial symbiosis opportunities in Rudniki based on the interest level of relevant industries

Industrial symbiosis opportunity	Source(s)	Receiver(s)	Interest score[a]
Use BF[b] slag as raw material	Steel	Cement	5
Use limemeal as raw material	Cement	Minerals	4.5
Use other materials (BOF[c], Laddle, dust mass) as raw material	Steel	Cement	3.5
Use steel slag and $CaCO_3$ for wastewater treatment	Steel & Minerals	Engineering[d]	3.5
Combined health & safety trainings	NA	All industries	3.3
Use coke breeze as raw material	Cement	Steel	3
Extra capacity of ball mills and drying facility	Cement	Minerals	3
District heating network	All industries	community	2.5
Collectively provide electrical flexibility	Minerals	Grid	1

[a] aggregated result of interest, [b] Blast Furnace, [c] Basic Oxygen Furnace, [d] Local office of the engineering company (Engineering industry) was not approached for surveys as they were not part of the case study

The first opportunity was already in place, but the two companies did not engage in a direct contract at the start of the case study. By the end of the case study, a legal contract was finalised between the two companies to continue the supply of BF slag from steel to cement.

Three industrial symbioses are further explored in Chapter 4 involving; supply of lime meal from minerals to cement, supply of slag from steel to cement, and the supply of scrap metal and plastics from cement to steel.

3.2 LAVÉRA (FRANCE)

The Lavéra cluster lies in the South of France as shown in Figure 3-3. The industry sectors of chemicals and steel make up the Lavéra cluster in France. The industrial site of chemicals is located in the Lavéra Chemical Park and the steel site is located in Fos-sur-Mer.

Figure 3-3: Location of Lavéra cluster

3.2.1 Cluster Dynamics

The Marseille-Fos region of France is rich in industrial activities and has a long history of socio-ecological evolution that shows strong relationship between different stakeholders at different points in time (Mat et al., 2016). The culture of industrial symbiosis has embedded itself in the industrial port and has resulted in the formulation of new entities that are exclusively catering to closing material loops and bringing various stakeholders of the region together. In the case study, the cluster is called as the Lavéra cluster because chemicals Lavéra site is the lead site and steel in Fos is the satellite one. However, the region of Marseille-Fos is the larger industrial area where both industries operate. In the following section the partners and the public-private association (PIICTO) is introduced.

3.2.1.1 Social

Chemicals Lavéra – lead site

Chemicals site is located on the coast of the Etang de Berre, next to the port of Marseille. The refinery at Lavéra is a joint venture and supplies fuel by pipelines into France, Switzerland and Southern Germany (*Joint Ventures*, n.d.). Lavéra refinery spans over an area of 650 ha and refines crude oil and produces chemicals, two complementary activities benefiting from significant synergies. The refinery is one of the most modern in France and is also the first in the south east of Europe with an annual processing capacity of 10 million tonne per annum of crude oil. It has a set of comprehensive units and high flexibility, which allows it to manufacture the wide range of oil products used by the general public, industry and in transport. Downstream of the refinery, the chemical site converts the light distillate fraction (ethylene, propylene, etc.) and then converts these to plastics and a variety of chemical intermediates.

The history of Lavéra industrial site began in 1933 with the installation of the British Petroleum refinery, which was followed by the construction of a large petrochemical complex. In 2011, a chemicals company partnered with Petrochina for trading and refining activities of chemicals. All chemical activities were grouped under the chemicals company in Lavéra. On 1 November 2014, two new legal structures were created.

The Lavéra site employs more than 1,000 people (chemicals and Petroineos) and hosts several parent companies: chemicals, Arkema and Total Petrochemicals France and subsidiaries (50/50 a chemicals company and Total Petrochemicals France): Naphtachimie for olefins and butadiene, Appryl for polypropylene, and Gexaro for benzene. chemicals subsidiary also owns 50/50 of Oxachimie with Arkema, which produces heavy alcohols.

Steel Fos – Satellite site

Steel Fos owns an area of 16 sq. km in the Fos-sur-Mer, while half of it is covered by a national park. The steel plant employs 2,500 personnel.

PIICTO (Platform for Industry and Innovation at Caban Tonkin)

The PIICTO project was launched by several stakeholders in the industrial port area of Fos in consultation with the port of Marseille Fos, Union of Chemical Industries, local authorities and the Chamber of Commerce & Industry Marseille Provence, with the support of the government, the ADEME (French Environment and Energy Management Agency) and the Provence-Alpes-Côte d'Azur region (PIICTO, 2018). PIICTO provides a platform for industrial in the Fos region to collaborate and move towards closing material loops.

Steel Fos and Chemicals Lavéra have existing ties through the human resource department of both companies. This program concerns personnel "mobility", which refers to switching of employees one company to another from time to time. For the moment, there is only one employee from the Human Resources department, who works for both chemicals and steel under this 'mobility' program. This is being done because steel and chemicals have similar needs in terms of employee support services.

3.2.1.2 Legal

Between the industry partners; chemicals and steel do not have any direct written contracts. However, both industries have waste management contracts with the third industry partner from the engineering sector. The chemicals company is located on a chemical park and shares park management services with other companies situated within the chemical park, e.g., combined security system, shared fire brigade service, intranet platform for sharing information, shared wastewater treatment plant, shared loading and unloading dock, shared service for collection of non-hazardous waste, shared information platforms regarding changing regulations and environmental performance on site and a water bottling plant where CO_2 from the chemicals operations is used by a third party.

Steel Fos also engages with neighbouring industries on different fronts for energy and resource efficiency. For example, with Ecocem; a concrete mix producer, who uses granulated slag from steel Fos plant's blast furnaces as raw material. Steel Fos also transports water to Ecocem. By-products from Steel Fos are constantly reviewed for valuation, e.g., tars are sent to Spain, in order to make electrodes for electric ovens.

Steel and Chemicals regularly collaborate with Grand Port of Marseille Mediterranean (GPMM) concerning land use activities. Both Steel Fos and Chemicals Lavéra, use the services of ADEME for advice on energy efficiency. From a regulatory point of view, Steel and Chemicals are both affected by the same regulations. The concerns of stricter regulation on carbon emissions is a demanding issue for both partners.

During the case study, the managers from the Chemicals Lavéra site were invited to the Steel site in Fos. Different industrial symbioses were discussed and both parties showed interest in further investigation of these opportunities. As a result a non-disclosure agreement was signed between the partners, which would allow them to share technical details about their processes with each other.

3.2.1.3 Economic

Chemicals and Steel are not currently engage in collaborative activities that bring economic benefits to the partners. There have been certain considerations to sell tar produced at the site of Chemicals to Steel but the project was not realised due to different quality requirement by Steel Fos plant. During LESTS interviews, it was realised that the price of energy has played a major role in subduing the efforts to engage in industrial symbiosis in Marseille region of France. The price of installing new infrastructure to connect the two industries, or the transport of material is deemed too high as compared to buying primary raw materials and fuels (business as usual), therefore many projects for energy or fuel efficiency have been shelved in the past few years. During LESTS interview with Steel Fos, it was pointed out that gas pipe connection between the two industries will cost 1 million euros for every kilometre of pipe, considering these high costs, there is a need to look for highly valuable exchanges between the two industries to outweigh the costs of setting up the infrastructure for industrial symbiosis.

3.2.1.4 Spatial

Spatial characteristics of Chemicals Lavéra and Steel Fos plant are very important when considering their potential for industrial symbiosis. Chemicals Lavéra is situated within a chemical park, while steel Fos is an independent plant on privately owned land. Distance between them is less than 20 km; approx. 10 kilometres via sea and 18 kilometres via road.

The area surrounded by steel Fos plant is regulated by GPMM. Any plans to change the current land-use have to be communicated to GPMM to acquire a permit to implement these changes. The steel plant is surrounded by sea on the southern and western side (Figure 3-4), the northern end of the steel plant is covered by natural reserves. The only possibility to collaborate involving material transport is via the Western side of the plant. Another significant spatial aspect of the Port of Marseille is the location of naval base, which restricts the installation of wind turbines in the close vicinity of steel Fos-sur-Mer plant.

Distance between chemicals Lavéra site and steel Fos-sur-Mer site

- Via road = 18 km
- Through sea = approximately 8 km

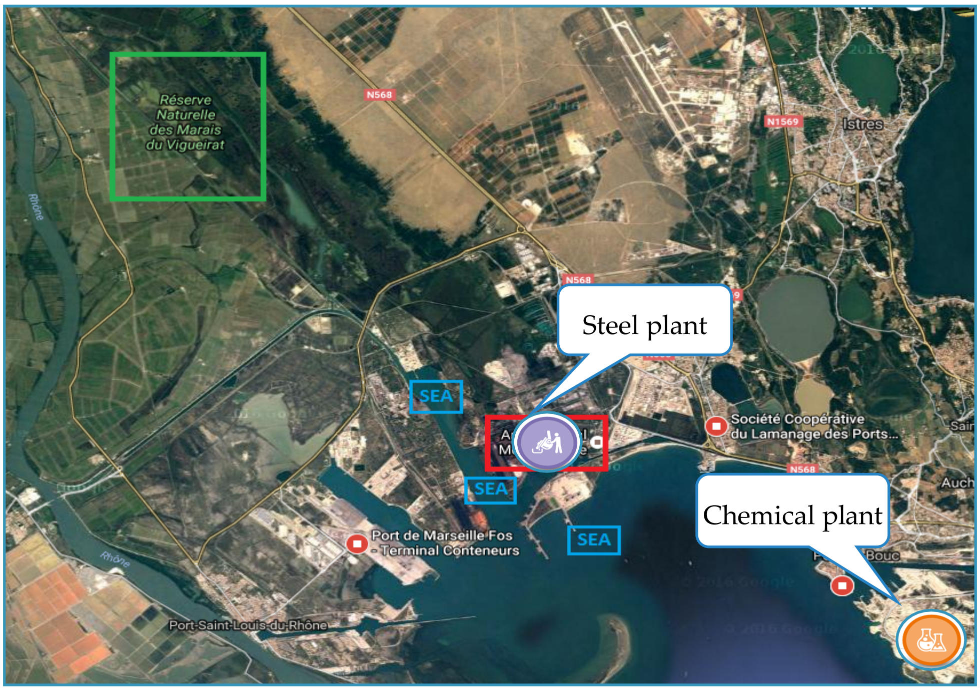


Figure 3-4: Spatial setting of Steel Fos-sur-Mer plant and Chemicals Lavéra site

Chemicals Lavéra is situated in a chemical park, which is divided into two sections. One side is dedicated to the refinery and the other to chemical production. The businesses present on the park are not all owned by the chemicals company (the ownership structure of businesses is discussed under the Legal aspect). A joint venture between two companies, Naphtachimie, is in charge of maintaining combined grounds on Lavéra site. In the LESTS interview it was pointed out that chemicals Lavéra might prove a challenging site to install new infrastructure because of the presence of third parties, use of access-routes by other companies and special consideration of health and safety regulations.

3.2.1.5 Technical

Both industries are interested in optimisation of steam networks, energy co-generation systems, district heating network, combined wastewater treatment and valuation of waste. However, spatial constraints and insignificant economic gains from substituting primary materials by secondary materials have resulted in little or almost no technical collaboration between the two industries.

Both industries were approached by PIICTO to be connected to the steam network, however, the costly pipeline that has to reach the industries became a hurdle. For steel the connection was to be provided from the western side and a pipeline had to be installed through the sea. For chemicals Lavéra, the distance to the originally planned steam network imposed even higher costs due to the distance.

3.2.2 LESTS Outcome

Marseille-Fos region shows the long history of collaboration between different stakeholders belonging to both public and private domains. The recent large scale industrial symbiosis activities involve infrastructure based symbioses, such as the power to hydrogen network and the steam network (PIICTO, 2018). The Marseille-Fos region can be defined as initially a **self-organised** symbiotic network that has seen different interventions from public authorities during its lifetime (Mat et al., 2016). Now, due to the presence of PIICTO as a facilitator for circular economy in the region, the industrial symbioses can be defined as **Facilitation – collective learning.**

On the smaller scale, the Lavéra Chemical Complex provides many examples of material and energy exchanges between different entities located on the chemical park. In relation with the industrial symbiosis dynamics, the Lavéra chemical complex depicts the industrial symbiosis as a result of **organisational boundary change** (Boons et al., 2017). As with many other chemical complexes, the ownership has changed and evolved into more complex legal structures over the years. Hence the existing ties between different plants can now be identified as industrial symbiosis, which previously could have just identified as material flows between different processes. Furthermore, based on the existence of PIICTO in the Marseille-Fos region, that is responsible for invigorating symbiosis with the mode of sustainability, the region shows a move from a **weak to strong sustainability**.

According to the three stages of industrial symbiosis, as defined by Chertow and Ehrenfield (2011), the Marseille-Fos cluster shows an advanced stage in the development as a complex system, where symbiosis has been **institutionalised and embedded** in the public-private and private sectors of the region.

3.2.3 Symbiosis Opportunities

The active role that the chemicals company played in driving the symbiosis detection in the Lavéra cluster resulted in the identification of seven symbiosis opportunities, which are provided in the annex (Table A-4). The prioritised list of symbiotic opportunities is provided in Table 3-2. As it is visible that half of the opportunities involve improved energy and material utilisation on individual site of the industry partner. This is a direct result of the distance between the two industrial partners.

Table 3-2: Shortlisted industrial symbiosis opportunities in Lavéra based on the interest level of relevant industries

Industrial symbiosis opportunity	Source(s)	Receiver(s)	Interest score[a]
Use COG[b], BFG[c] and BOFG[d] for methane production[e]	Steel	NA	4
Use spent coke as reductant	Chemicals	Steel	4.5
Electric vehicles on site for use by employees and visitors[e]	NA	NA	4
Install solar panels[e]	NA	NA	4
Use COG, BFG and BOFG in boilers	Steel	Chemicals	3 - 3.5
Use Naphtha-lined gasoil	Steel	Chemicals	2.5 - 3

[a] aggregated result of interest, [b] Coke Oven Gas, [c] Blast Furnace Gas, [d] Basic Oxygen Furnace Gas, [e] resource efficiency proposals that do not require symbiosis

The opportunities related to the use of Naphtha-lined gasoil and coke are explored further in chapter 4.

3.3 HUMBER (UNITED KINGDOM)

In 2000, Business Council for Sustainable Development-United Kingdom (BCSD-UK) took up the responsibility to promote industrial symbiosis in different industrial regions of UK. BCSD-UK launched the National Industrial Symbiosis Programme-UK (NISP-UK) in 2005 and selected three pilot regions in UK to foster bottom up industrial symbioses in the region. These three pilot regions were; Humber, West Midlands, and Mersey Banks. International Synergies Ltd spearheaded the NISP-UK. The funding for the programme ceased in 2014 but the program is still kept alive by International Synergies Ltd.

Figure 3-5: Location of the industries in Humber cluster

The Humber region, located on the east coast of Northern England, UK (as shown in Figure 3-5), is one of the key areas targeted by the UK Government to achieve national carbon emissions reduction targets by implementing circular strategies (HM Government, 2009). Indeed, it hosts one of the largest and busiest port complexes in the UK (Velenturf, 2017) and the region is one of England's most diverse industrial system (Jensen, 2016), with one of the highest concentration of food processing, chemical, fuel and power production facilities (Penn et al., 2014). It is also a strategic area for the UK's energy supply, hosting a (petro)chemicals sector worth £6bn per year (Humber Local Enterprise Partnership, 2014). As a result, it is responsible for 27% of UK's total CO_2 emissions emanating from industries subject to Integrated Pollution, Prevention, and Control regulations (Penn et al., 2013) derived from (Yorkshire and the Humber Regional Committee, 2010). It is thus a priority to reduce the region's environmental footprint while preserving industries' competitiveness and the prosperity of the local society.

The LESTS survey of the Hull Cluster was filled out by interviewing a manager of each industry partner on site in close collaboration with the PhD student working at each company. The information collected via LESTS survey was processed to analyse the existing platforms and activities that the partner industries could collectively benefit from. Also the information in the surveys helped to propose symbiosis activities to the industry partners.

3.3.1 Cluster dynamics

The following synthesis is based on the interviews and surveys that were conducted with the industry partners in the Humber region. The secondary data were collected from the website of International Synergies Ltd and the work of Mirata (2004) and Bailey & Gadd (2017) (Bailey & Gadd, 2016; International Synergies, n.d.; Mirata, 2004).

3.3.1.1 Social

Efforts to develop industrial symbiosis in Humber region can be divided into two time periods. Before the start of NISP-UK and after NISP-UK. Before the NISP-UK was launched, there were proposals of large infrastructure symbiosis in Humber that related to combined heat and power (Immingham CHP), linking of chemical plants on each side of the Humber River via an underwater pipeline ("Humber-bundle") and other material focused symbioses between chemical industries in the region. All these initiatives promised substantial environmental, social and economic benefits for the region (Mirata, 2004). However, these proposals were unable to incite interest from the local businesses. One reason is attributed to the entities that spearheaded the program then. It was a major chemical company who proposed the idea of the CHP based on their experience with the Business Council for Sustainable Development in Gulf of Mexico. The chemical business with BCSD-UK initiated the Humber Industrial Symbiosis Programme (HISP). The financing of the team that led the initiative was done by the fee paid by the signatories from profits of possible symbioses. However, this created a misunderstanding among the diverse local businesses who understood that the symbiosis activities were better suited for the large industries (Mirata, 2004).

Towards the end of 2001, due to lack of funding the progress of HISP was almost halted. In 2003, the program was relaunched as a pilot project of NISP-UK and this time the lessons from the previous experience were taken into consideration. This time the programme was headed by the Regional Development Agency. The top-down approach was replaced with a bottom-up one and focused on industrial symbiosis of different scales (Bailey & Gadd, 2016; Mirata, 2004). Link2Energy Ltd ran the industrial programmes in Yorkshire and Humber on behalf of International Synergies Ltd. Initially, Link2Energy Ltd relied on public funds but from 2012, Link2Energy Ltd developed its own independent commercial programme *Re:Sourcing UK* with a focus on high-value opportunities and innovation (Bailey & Gadd, 2016).

From the exploration of the literature on HISP, it is evident that the more successful efforts for developing industrial symbiosis were bottom-up and did not rely on ambitious projects that required major infrastructure development. All the industries in the Humber cluster have been approached by the representatives of different industrial symbiosis programs, however, they did not report any symbiotic activity that was being managed by a third party or that was identified through the help of a third party.

A company belonging to the engineering sector is responsible for waste management at the Chemicals Hull site. Recently Chemicals Hull had decided to shut down a plant and the engineering company was given the contract to clean the site, demolish the unit and also decontaminate the site. The engineering company is responsible for selling waste derived fuel to Cement South Ferriby and managing the waste from kilns after the fuel has been burnt. The engineering company's expertise in applying for environmental permits and existence on Hull site since a long time, provides a level of trust among the industry partners.

Following is a brief overview of the industrial sites that took part in the Humber cluster.

Minerals Melton – Lead site

Industrial production started at Melton Quarry in 1921 under the ownership of W. Marshall (Hessle) Ltd, supplying chalk slurry to the nearby Humber Cement Works. In 1937 production of the first non-cement grade (an agricultural chalk) followed the introduction of a farming subsidy for such applications. Further capital investment expanded the range of products. By 2002 the plant had expanded to include a marble processing plant, a coating plant and a granulating plant on a modernised site. The marble processing plant has been decommissioned, In 1958 Blue Circle took over the site and in 1987 the Melton plant was divorced from the Humber Cement Works. The latter closed in 1981 and Melton Plant became fully independent. In 1989 Blue Circle and Croxton + Garry Ltd formed a joint venture, merging their industrial minerals operations. The minerals company who was part of the case study took over in early nineties, site is nowadays 100% owned & operated by the minerals company.

The minerals company has two sites in the Humber cluster with 3 km between them; the two sites are very different from a business point of view. One is in Melton and the other in Humber. Minerals Melton and Humber implemented ESOS (EED reporting under UK system) and carried out the analysis for 5 of their plant which cover more than 90% of the energy consumption of minerals UK. In the past, minerals used to sell electricity to the Cement South Ferriby, as they were a tenant at their Humber side, but this activity has been discontinued. In the year 2015, Minerals Melton plant had a production of approx. 160 k tonnes, about 72% of the product consisted of different chalk powder products.

Minerals Melton (North) is a typical quarry site and sets itself in minerals market. Melton plant operates both a dry and a wet process, producing a total of 16 different products, out of which 12 are dry powders and 4 are chalk slurries. Earlier minerals Melton produced powder for the cement industry, which is now discontinued. Minerals Melton quarry has quarrying permission till 2044 but there is potential for a 100 more years. Melton quarry site has 34 employees and there are 20 employees in Melton office.

Minerals Humber (South) The main process at minerals Humber site is mixing and preparing chemicals for rubber used in tyre industry. There are 43 employees, including temporary workers, at the minerals Humber site.

Chemicals Hull – Satellite site

As gathered during the LESTS survey, the Chemicals company arrived at the Saltend Chemical Park in 2008. The Ethylene Acetate plant already existed under the ownership of British Petroleum. The Chemicals Hull plant employs 26 people. Chemicals Hull is a satellite site of the main site in Antwerp, Belgium. At Hull the core product is Ethylene Acetate (EtAc). EtAc is an intermediate chemical used in the manufacturing of a wide variety of everyday household products such as perfumes and printing inks; paints and varnishes; and flavour and odour enhancers.

Along with the infrastructure of British Petroleum, Chemicals Hull also inherited the existing contracts with other parties, including the waste management contract with an engineering company. Chemicals Hull takes part in the Saltend Chemical park management, led by BP chemicals who still hosts the park.

Cement South Ferriby – Satellite site

The Humber estuary has a 70 year long history of cement production. Cement South Ferriby plant makes its cement using local chalk and clay taken from different areas of the same quarry. Around 3,000 tonnes of chalk and 1,000 tonnes of clay are needed each day. Two kilns heat the raw materials to 1400 °C. The gases and dust from the kiln are subjected to an intense filtering and scrubbing process before being safely emitted to the atmosphere.

While traditional fossil fuels – coal and petcoke – are still in use in the kiln, South Ferriby is increasingly using more sustainable and cost-effective alternative fuels. Since 2002, Cement South Ferriby has been successfully using secondary liquid fuel made from industrial liquid wastes that cannot be recycled. The plant delivers its vital end-product by road over a wide area of eastern, central and northern England. It also ships cement from Grimsby to Leith on the east coast of Scotland.

In total, the company's annual contribution to the local economy through wages, rates and the buying of services adds up to some £10 million (*CEMEX UK | South Ferriby Community | Helping to Build A Greater Britain*, n.d.). The Cement South Ferriby has 70 employees.

3.3.1.2 Legal

None of the member industries are engaged in a symbiotic relationship with other partners present in the Humber cluster. The only legal contracts between the members were written with the engineering company to acquire their services for waste management. However, Minerals and Chemicals do engage in different collaborations with neighbouring industries. For minerals, important among them is a waste management company, who is also provided electricity through the electricity connection of Minerals. Together, Minerals and the waste management company received the permits for installation of five wind turbines in Humber region. However, the subsidy scheme changed and the support from the public funds was reduced. During the LESTS interview, Minerals was only interested in the installation of two turbines on the land owned by the waste management company. During the course of the case study, no updates were reported on the installation of the wind turbines. By the end of the project, Minerals' interest in the wind turbines was significantly diminished.

Other important legal aspects of significance include the existing environmental permits of the Minerals and Cement site. For example, during the interview it was identified that a reject stream from Minerals can feed as raw material for cement plant. Currently the reject stream is used for land reclamation (landscaping) in Melton quarry. On the other hand, Cement is interested in finding innovative uses of the cement kiln dust and they wanted to offer this material for landscaping at the quarry site of minerals. The cement kiln dust has very fine particle size and does not meet the criteria for the material that can be used for land reclamation at the site of Minerals. However, upon further investigation it was realised that the environmental permit issued to Minerals binds them to use only the same material originating from Melton quarry. The environmental permit is binding till 2042 and minerals did not show an interest in carrying out the long and winding procedure to reapply for the permit before its expiry.

Another detail about the legal aspect led to identification of a symbiosis opportunity during the interviews with Cement and Chemicals. It was reported that Chemicals Hull plant produces a liquid waste stream that is currently sent to a boiler owned by a third party on the Saltend Park. It is a light fuel type, which is burned to produce steam. The handling of this Primary Liquid Fuel (PLF) is carried out by the engineering company. Additionally, Cement South Ferriby has a permit to use waste as fuel in the cement kilns. Currently, only 80% of the fuel burnt in cement kilns is based on waste. The liquid waste stream from Chemicals can provide an opportunity for Cement to replace the remaining 20% of the primary fuels with the PLF stream from Chemicals.

3.3.1.3 Economic

A number of economic incentives exist for the industries to engage in collaboration that can result in carbon emission reductions. For example, Minerals can benefit from a £ 180 000 rebate under a levy for energy use reduction. However, in 2014, Minerals couldn't reach the reduction targets and had to release offset carbon credits of £ 30000.

For Cement the economic incentive lies in finding innovative ways to divert cement kiln dust away from landfills. For Chemicals the incentive lies in finding an alternative way to utilise their PLF stream, as it is a stream that causes them to pay a high price for the steam that they receive from the boiler. The reason being the quality of the PLF causes the boiler to perform at subpar, hence raising the cost for Chemicals to receive steam in return.

It shows that either due to the burden of stricter public regulations or the general benefit of collaboration to achieve energy and resource use efficiency, the industrial partners have sufficient economic incentive to collaborate and engage in industrial symbiosis in UK Humber cluster.

3.3.1.4 Spatial

To propose symbiosis activities that will require flow exchanges between the industries, the physical distance between their locations is paramount. The road distances between the industrial sites are shown in Figure 3-6. All distances are calculated from the location of Minerals Melton plant. This is solely done because minerals took the lead to represent the industries in the Humber cluster of the case study.

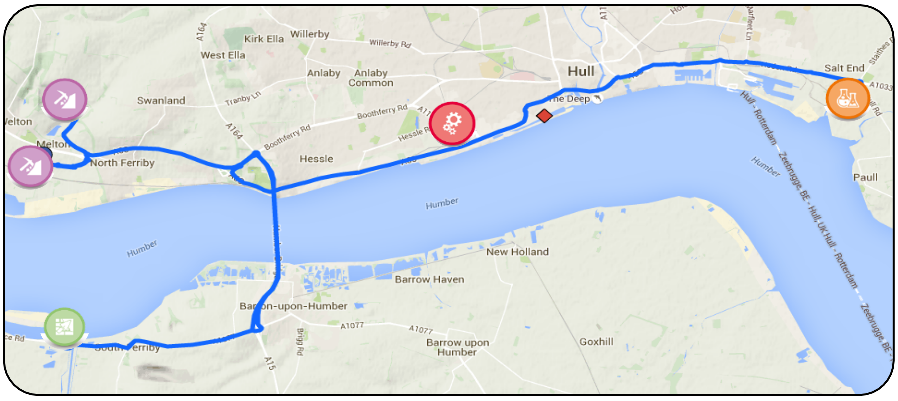


Figure 3-6: Location of the different industries in the Humber cluster (UK)

Distance from minerals Melton plant to other industrial sites are as follows:

- Cement South Ferriby = 21 km
- Chemicals Chemicals (EtAc plant) = 23 km

The industry partners in the Humber cluster have two distinct spatial characteristics. Chemicals Hull is located in a chemical park; the Saltend chemical park, and Minerals and Cement plants are located closer to the excavation sites of their respective raw materials. Cement and Minerals own the land and operate independently, while Chemicals shares certain facilities with third parties present on Saltend chemical park, e.g., wastewater treatment, security services, grounds' care, shared access routes within the chemical parks, etc.

The Minerals company has two plants in the Humber cluster, which lie 3 km apart; a quarry and plant at Melton and a processing plant in Humber. Cement owns land in South Ferriby closer to the availability of raw materials, i.e., sand and chalk. Minerals, Cement and Chemicals have free land on their sites, which can be used for industrial symbiosis project(s).

Minerals sends their raw material and are duty bound to ensure land reclamation in their quarry. minerals uses flint and the aforementioned reject stream for landscaping purposes. Cement owns a landfill on South Ferriby site, however, their interest lies in keeping valuable by-products out of the landfill.

Another important spatial aspect of Humber region for prospective installation of wind turbines is that the area serves as feeding grounds for migratory birds. Also the community in Humber region opposes the insallation of wind turbines because of the negative impact wind turbines have on the real estate prices.

3.3.1.5 Technical

All the issues that were raised during the LESTS interviews as facing the industries have available technological solutions. However, the conventional end-of-pipe technologies available in market are considered extremely expensive. This leaves room for innovation and industrial symbiosis between the industries. Since there are no existing symbiosis cases whose technical details could be explained here, the proposals and their technical details are mentioned in chapter 4.

3.3.2 LESTS outcome

Humber has a long history of public interest to cultivate industrial symbiosis is the region. Legal entities like International Synergies Ltd and Link2Energy provide a reference point for searching for symbiosis. This shows a strong commitment to the objective of industrial symbiosis in the region. Based on the relevance of existing entities in the Humber region responsible for invigorating symbiosis with the mode of sustainability, the region shows a move from a **weak to strong sustainability**.

While observing the environmental benefits, it is reported that from 2003 and over the subsequent 5 years, HISP engaged with 700 companies in Yorkshire and Humber and documented CO_2 reductions of 780,000 tonnes per annum for its clients and a reduction of 1,400,000 tonnes in material being landfilled (Bailey & Gadd, 2016). This shows a strong positive correlation between industrial symbiosis and environmental benefits. As HISP was initiated and supported by the local agencies, this points to a **strong sustainability** (in relation to canons of sustainability (Baas & Boons, 2004a)) as well. It shows that holistic thinking has emerged in the local governments to move towards a sustainable future.

In terms of dynamics in the Humber region, the cluster follows an interesting evolution. Starting from the collaboration of public and private organisations to start large infra-structure based symbiosis, that could be identified as a combination of **self-organised and facilitation – collective learning**. As the development of NISP-UK initiated a move to bottom-up symbioses, the dynamics show a move to a **facilitation – brokerage**. Finally, as the funding for NISP-UK has been discontinued, the cluster is pushed to follow a **self-organisation** pathway for the industrial actors in the region.

Self-organisation has resulted in the industrial members to look for symbiotic partners on their own, without relying on a local entity. However, the EPOS project, which this case study is part of, can be viewed as a facilitator that has helped to identify symbioses between the industries in the cluster. However, since all the industry partners face different pressing issues, their solutions also needed to be varied. For Minerals, the interest lay in reducing their energy consumption, specifically electricity. For Cement, Cement Kiln Dust (CKD) posed the biggest challenge since it requires them to store it on their site or send it off-site to a landfill, which has a very high tax. Chemicals site in Hull did not mention a pressing issue, however, an interesting by-product consisting of primary liquid fuel (PLF) was identified as a valuable stream for symbiosis during the interview. At that time this PLF stream that was sent to an on-site boiler of a third party in return for expensive steam.

According to the three stages of industrial symbiosis, as defined by Chertow and Ehrenfield (2011), the Humber cluster shows an advanced stage in the development as a complex system, where symbiosis has been **institutionalised and embedded** in the public-private and private sectors of the region.

3.3.3 Symbiosis opportunities

Although the industry partners are well connected via major transport routes, and lie in a radius of less than 25 km apart from each other, the spatial distance is not optimum for sharing equipment and facilities. A number of other opportunities were proposed in a preliminary list to the industrial actors, see annex (Table A-6). After a year, the opportunities were prioritised based on the level of interest from the relevant industries. The resulting prioritised list is provided in Table 3-3.

Table 3-3: Shortlisted industrial symbiosis opportunities in Humber based on the interest level of relevant industries

Industrial symbiosis opportunity	Sender(s)	Receiver(s)	Interest score[a]
Use PLF[b] stream as an AF[c] in cement kiln	Chemicals	Cement	3.5
Reuse calcium carbonate rich reject stream	Minerals	Cement	3
Cement Kiln Dust	Cement	Minerals	3
Capture CO_2 and use it in a greenhouse	Cement, Minerals	Local community	2.3
Reuse spent catalyst	Chemicals	All industries	2.3
Install micro-turbines on the river Humber	All industries	Local community	2.3
Organise combined health and safety trainings	Engineering	All industries	2.3
Recover heat from exhaust gas	Minerals	Cement	2

Recover heat from condensates	Chemicals	All industries	2
Valorise low temperature heat with district heating network	Cement	Local community	2
Use excess cooling capacity	Chemicals	All industries	1.7
Recover heat from exhaust gas	Cement	All industries	1.6
Reuse cardboard, plastic, rubber wastes	Cement	All industries	1.3

[a] aggregated result of interest, [b] Primary Liquid Fuel, [c] Alternative Fuels

The first three symbiosis opportunities are further elaborated on in chapter 4.

3.4 VISP DISTRICT HEATING AND COOLING NETWORK (SWITZERLAND)

43% of the total energy use in Europe is consumed for heating and cooling purposes of households (European Commission, 2011). Hence, heating networks that provide households with industrial waste heat provide a much-needed avoidance of carbon emissions. One of the example cases in the case study on industrial symbioses is the network in Visp (Switzerland) where a biotechnology company provides waste heat for district heating and cooling to the city of Visp. The other one is the district heating network in Dunkirk, being fed by the waste heat of a steel plant.

In this section, Visp District Heating and Cooling Network (DH&CN) is analysed using the LESTS framework. The cluster dynamics are explained and a conclusion on the sustainability status of the symbiosis is made at the end.

The Visp DH&CN started in 1989 between the biotechnology company and the city of Visp. It covers an area of 6.5 sq. km and has 147 connections: 24 to company houses, 10 to public buildings and 113 to private houses in the district. The flow-rate of water running through the district heating network was 30-210 m³/h and the quantity of heat carried was 20 GWh/a. The installed capacity of the DH&CN is 12 MW.

Figure 3-7: Location of the Visp district heating and cooling network

The heating-temperature in the DH&CN is maintained around 70 °F (18 °C) and fed directly from the company, as shown in Figure 3-8. The cooling-temperature is set around 40 °F (8 °C). The two temperature levels are typical of the fifth generation heating and cooling networks. Authors of (Buffa et al., 2019) defined the Visp DH&CN as a bidirectional energy flow – unidirectional medium flow network. The DH&CN uses waste heat from a sewage of the industrial site as a heat source and de-centralized heat pumps are used in the individual residential buildings to raise the temperatures sufficiently high to operate the floor heating systems (Bünning et al., 2018).

The installed capacity of Visp DH&CN is 12 MW and the heat demand in a heating season is 20300 MWh. Some 130 public and private buildings are connected to the district heating network ("EnAlpin AG-District Visp," n.d.).

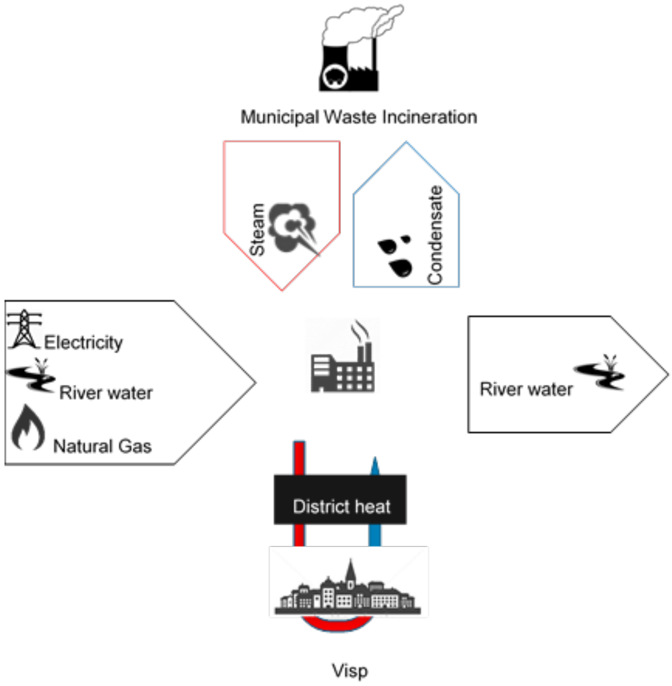


Figure 3-8: Temperature and material flows in Visp District Heating Network

In 2010, the network's length was extended by 1 km and 2 more private houses were given a connection to the DH&CN. The flow-rate of water was increased to 30-500 m³/h and the quantity of heat carried was increased to 10 GWh/a.

The EnAlpin AG acquired the management of the DH&CN from 1 February 2013. Responsibilities of EnAlpin AG include reading of heat meters, guiding the financial accounting, customer billing and care. Further, the administrative work such as correspondence, entertaining, and renovation work on behalf of the Visp district. Fernwärme Visp AG operates the DH&CN. The industrial site Visp and the municipality of Visp share the ownership of Fernwärme Visp AG.

3.4.1 Cluster Dynamics

During the course of the case study, the information about the Visp district heating and cooling network was provided by an SME located in Sion, Switzerland. Learning effects on the Visp network were investigated by the SME in its liaison role with the regional authorities.

3.4.1.1 Social:

Social aspect of Visp DH&CN is explained by first enlisting the stakeholders of the DH&CN and then the historical overview of their collaboration regarding DH&CN is explained.

The list of stakeholders directly involved with VDH&CN is given as following:

1. **Fernwärme Visp AG**: Fernwärme Visp AG is a private shareholder company, established in 1989. It is responsible for running the Visp DH&CN. It is co-owned by the biotechnology company and the city of Visp. All decisions regarding Visp DH&CN are made by Fernwärme Visp AG.

2. **The company**: The industrial site is the shareholder of Fernwärme Visp AG. The company proposed the project in the '80s and provided the technical support for setting up the heating network. The industrial site is still feeding heat into the network.

3. **City of Visp**: The local body representing the community of Visp. City of Visp owns half of the shares of Fernwärme Visp AG.

4. **Local hospital in Visp**: The hospital in Visp, along with the City of Visp and The industrial site were the first shareholders of Fernwärme Visp AG, also the first customers of Visp DH&CN.

5. **A private pension fund**: One of the first customers of Visp DH&CN was the pension fund of the company.

6. **Elektrowatt:** Elektrowatt was a third party contractor who was hired by the company and city of Visp to carry out the feasibility study of the Visp DH&CN.

7. **EnAlpin:** EnAlpin is a local electrical grid operator, hired by Fernwärme Visp AG to carry out the administrative tasks for Visp DH&CN. EnAlpin AG was created when the biotechnology company sold its power production facilities to private owners. Since 2013, EnAlpin does all administrative tasks regarding the Visp DH&CN.

8. **Customers:** The buildings connected to the DH&CN belong to either the company pension fund, public (city of Visp, train station, etc.), and private owners (houses or apartments). The proportions are around 80% private buildings (113 buildings), 7% public (10 buildings) and 13% the company pension fund (19 buildings).

The social embeddedness of the two main stakeholders; the company and city of Visp has a long history. the company was founded in 1897 in the small Swiss town of Gampel, situated in the canton of Valais. Initially the company produced electricity used for manufacturing chemicals, such as calcium carbide. In 1909, the company moved to Visp, where it started to transform itself from an electricity-generator to a chemical company to one of the leading suppliers to the pharmaceutical, healthcare and life science industries. The company is a major employer of the people of the Valais region. In Visp, almost 500 people from total population of almost 8000 are employed by the company.

The proposal for starting Visp DH&CN came from employees of the company, when a new head of the energy department of the company was appointed. During that time, the company AG had started to explore different options of heat recovery and energy savings. The head of the energy department carried out a site analysis for heat optimisation and found out that after site optimisation, the company still had waste steam at 3.5 bar. the company was also concerned about the upcoming new Swiss law on CO_2 emissions. It was proposed that a district heating network could help to improve the image of Visp city. This was the point of interest for the president of the board of the company Group was a strong proponent of district heating networks. He acted as a catalyst for the Visp DH&CN by backing the head of the energy department and his team in Visp. The proposal was quickly accepted by then mayor of the city of Visp.

The proponents of Visp DH&CN came together including the company's energy department and site management, backed by the president of the board of the business, mayor of city of Visp, the company pension fund (offering their buildings as first customers for the network) and hospital of Visp (managed at that time by nuns). Together they took the decision to form a shareholder company (Fernwärme Visp AG) and built a first central DH&CN pipeline connecting the company with the city and the hospital.

The city of Visp feared that if the proposal was brought to the community for a vote, they might be negatively influenced by the oil industry (competitors of Visp DH&CN). To avoid this, the partners decided to formulate a shareholder company and proceed with the setting up of the project. The process of putting the DH&CN in place was very quick. Elektrowatt was already active in Visp and had experience of building district heating networks. They were hired to carry out the feasibility study of DH&CN. Unfortunately, employees of Elektrowatt with knowledge of district heating networks left the company and rest of the work was carried out under the lead of the industrial site's engineers.

In the beginning, there was a miscommunication between the private customers and the DH&CN proposers. Most of the customers of the DH&CN understood that the new heating network would cost less than oil heating. However, the DH&CN promised that it would not cost more than the total cost of the old oil heating. Total cost includes cost of oil plus cost for revision of the oil heating, cost for the annual cleaning of the chimney, cost for the revision of the tank, etc. An article in 2017 also pointed to the persistent high price of the DH&CN in Visp as compared to the conventional fossil based heating systems (1815.ch, 2017). This example emphasises the need for clear and frequent communication between different stakeholder groups and also the need to include all stakeholders in the decision making process (Buffa et al., 2019).

The existing social networks have progressed through the years and formed into more formulised business connections. There are usual stakeholder meetings at the board level and annual shareholder meetings at Fernwärme Visp AG. There are two to three meetings per year between city council of Visp and the company's management; also there are ad hoc meetings whenever needed. Communication between stakeholders regarding Fernwärme Visp AG is formal and structured. However, for running operations of Visp DH&CN the consultation is very collaborative and informal.

There is a strong informal link between the community and because of the amount of locals employed at the company. For example, one of the members of Visp city council is a board member of Fernwärme Visp AG and is an employee of the company. The company manages the wastewater treatment infrastructure of Visp city and provides free heat for community swimming pool.

Visp DH&CN provides a good example of the importance of informal social networks between individuals for any symbiosis. Even if the partnership has not always been driven by economic gains (explained further under Economic aspect), 'a common wish' of all the stakeholders is the strongest push needed for a successful symbiosis.

3.4.1.2 Legal:

In 1989, the company's industrial site, city of Visp, and the local hospital founded the shareholder company Fernwärme Visp AG. The company was registered on February 1st, 1989 with a share capital of 500 k CHF (Swiss franc). At that time, the shareholders were the three founding organisations. The three shareholders gave the financial guarantees for the needed bank loan of approximately eight M CHF. The investment for capturing the waste heat from the industrial process was made by the company AG and amounted to 2.5 M CHF. Today, the city of Visp and the industrial site hold equal shares. Visp hospital is not a shareholder anymore.

The board of Fernwärme Visp is composed of four members; two representatives from city of Visp and two from the company. The president of Fernwärme Visp is member of the Visp city council and the vice-president is the site manager of the industrial site in

Visp. Administrative managing director of Fernwärme Visp is an employee of EnAlpin and the vice-manager is a member of the technical staff of city of Visp.

3.4.1.3 Economic:

Visp DH&CN connects to approximately 142 customers and has an annual turnover of around 2 million CHF with a net profit margin of around seven to eight percent. The joint company Fernwärme Visp AG buys energy/heat from the industrial site at agreed prices (around 1.2 million CHF in 2013/14 approximately equals to 67 CHF/MWh) and sells it to customers at agreed prices (79 CHF/MWh in 2013/14).

In the first heat supply contracts (until 2007), the price for the provided heat was linked to the oil price. The customers of the DH&CN had the guarantee, that connecting to DH&CN will not cost them more than what would have been the total costs for a classical oil heating. An oil price of 60 CHF would have balanced the costs for the DH&CN, but then oil prices dropped very quickly to 30 CHF and the three shareholders had to cover the losses over several years that amounted to around 500 k CHF/year (including bank loans and interest rates).

Since 2007, the price for the supplied heat is no longer linked to the oil price; still it marginally covers the costs of the DH&CN. This is not financially sustainable, as Fernwärme Visp AG is unable to achieve financial reserves for the time when parts of the DH&CN will finish their lifetime and will need replacing. Lifetime of the physical structure of the DH&CN was initially calculated to be 40 years.

3.4.1.4 Spatial:

Spatial proximity is a major driver for all industrial symbiosis project involving exchange of materials and energy. It has a fundamental role in minimizing costs and impacts of transport; in improving trust and cooperation among firms; and in facilitating the material exchanges (M. R. Chertow, 2000b; Hewes & Lyons, 2008; Jensen et al., 2011; Simboli et al., 2015).

Geographical proximity of the industrial site and the community of Visp clearly plays an important role in the proposal of the project. City of Visp is situated right next to the plant. This has also resulted in informal social connections between different stakeholders, creating a bond of trust. The social embeddedness, which results as a result of social networks has been a recurring theme of success of industrial symbiosis in literature (Boons & Janssen, 2004; Hewes & Lyons, 2008; Jensen et al., 2011) and can be seen to play an important role in the success of Visp DH&CN.

3.4.1.5 Technical:

The Visp DH&CN is classified as a fifth generation district heating and cooling system. With its separate pipelines for high temperature and low temperate network, it allows for heating and cooling of different building simultaneously. Visp DH&CN operates a high temperature (18 °C upstream) and a low temperature (8 °C downstream) water network with an installed power of 12 MW. Around 20 000 MWh energy is provided energy over a normal heating period. The high temperature network was built in 1989 and has a length of 6.5 km with a main pipe section of 200 mm. The low temperature network was started in 2010 and has a main pipe section of 400 mm. The reason to start the exploitation of the low temperature network has been the construction of the new train station in Visp and the linked need for cooling and heating.

For the first 14 years, the industrial site was responsible for technical management of the DH&CN and people of city administration took care of the business matters. During that time, neither the industrial site nor the city of Visp charged any fees for managing the

DH&CN. These were in-kind services offered by the two shareholders of Fernwärme Visp AG. As of February 1, 2013, Fernwärme Visp AG has mandated EnAlpin to carry out the administrative management. There have not been many technical problems when building the network but a few problems that arose due to technical issues are mentioned below.

- Improperly working leak detection systems;
- External corrosion of the pipes because of badly made isolation and/or damage of the isolation by stones/machines;
- Returning water (low temperature network) with a higher temperature than 40 °F (8 °C), which needed to be cooled down before injection into the industrial site production units. Reason behind this technological defect was the size of the heat exchangers in the houses. The installed heat exchangers were too large, thus there was not enough exchange of heat. Downsizing the heat exchangers in the buildings solved the problem.

3.4.2 LESTS Outcome

Based on the cluster dynamics that are enumerated in the last section, it can be deduced that the industrial symbiosis particular to the Visp DH&CN has emerged as a result of the self-organisation by the different actors. The industry and the public authority are the initial actors who initiated the plan to install a heating network. However, the benefit for the industrial partner was not the driving force. Hence, the dynamic can be classified as **facilitation - brokerage** by the public authorities. The public authorities created a market for the waste heat by installing the infrastructure and connecting the industrial waste heat to the public offices and buildings of the industrial site.

The information that was collected via the interview and the few secondary sources that provide information on the Visp DH&CN concerns only the district heating network and does not include industrial development of the region. However, because of the general commitment to work collaboratively in the Visp cluster and the formation of Visp Fernwarme that is categorised one of the modes of sustainability, the cluster can be classified to have **strong sustainability** characteristics.

According to the three stages of industrial symbiosis, as defined by Chertow and Ehrenfield (2011), the Visp DH&CN shows an advanced stage in the development as a complex system, where symbiosis has been **institutionalised** in the public-private partnerships in the region. It is to be noted that Visp DH&CN is a public-private partnership and the focus of the study was only the DH&CN. The businesses in the region were not studied, therefore this is a very limited conclusion.

3.4.3 Symbiosis Opportunities

The industrial site that provided heat for the Visp DH&CN was not part of the case study. The information at the flow level was never collected and no symbiosis opportunities could be proposed for the Visp cluster.

3.5 DUNKIRK DISTRICT HEATING NETWORK (FRANCE)

Dunkirk is an industrial port with shipyards, an oil refinery and iron and steel complex of ArcelorMittal, the steel industry, located in northern France, as shown in Figure 3-9. The annual report on the district heating networks in France (Auvergne-Rhône-Alpes I Bourgogne-Franche-Comté I Bretagne et al., 2016) published the information on the District Heating Network (DHN) in Dunkirk. According to the report, the Dunkirk DHN currently delivers nearly 140,000 MWh heat per annum to 13,469 customers through an approximately 40 km distribution network that covers a large portion of the city. The heat provides 60% of the customers from ArcelorMittal. Emissions of the DHN correlate to 0.11 kg of CO_2/kWh of the heat from the DHN.

Figure 3-9: Location of Dunkirk cluster

The DHN was originally designed to recover waste heat from the local steel industry, then Usinor (now ArcelorMittal). The recovered heat accounts for 80% of the total heat demand of the DHN. Following the addition of three cogeneration units at different locations and the commissioning of a second waste heat capture unit at the ArcelorMittal plant in April 2008, the percentage of recovered energy in the network has risen to 90%. Seventy percent of this recovered heat has a neutral impact in terms of CO_2, NO_x, SO_x, and other emissions. The installations were certified ISO 14001 in 2007.

Total installed capacity of the DHN is 100 MW (boilers and heat recovery) and these heat sources for DHN (shown in Figure 3-10) are,

1. Two 28 MW combined heat recovery units at ArcelorMittal.
2. A 13 MW gas/domestic fuel oil heating plant at the Dunkirk hospital, backed by a 4 MWe cogeneration unit.
3. An 8 MW gas/domestic fuel oil heating plant in the Glacis neighbourhood, backed by a 4 MWe cogeneration unit.
4. A 2 MW gas heating plant at the Paul Asseman swimming pool, backed by a 1 MWe cogeneration unit.
5. A 36 MW heavy oil heating plant at Ile Jeanty.

6. A number of auxiliary/standby gas/domestic fuel oil heating plants (6 MW).

The cogeneration units operate during the winter from 1 November to 31 March, in accordance with sales contracts with Électricité de France (EDF).

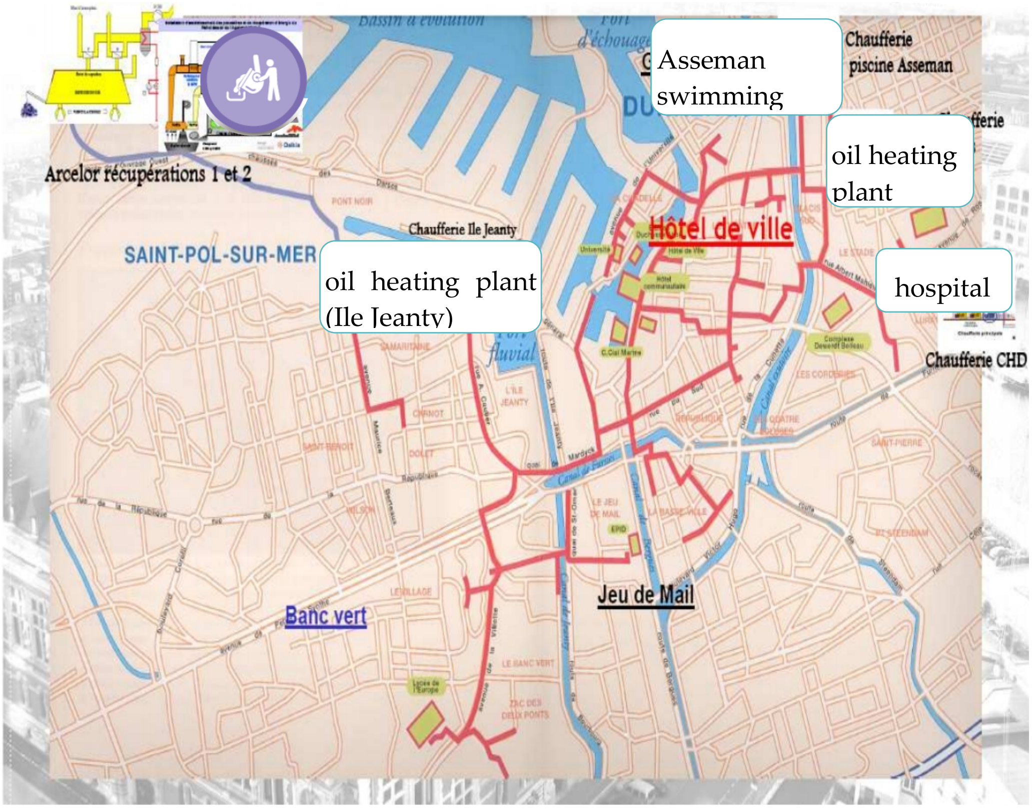


Figure 3-10: Location of different heat sources for Dunkirk district heating network

3.5.1 Cluster Dynamics

The information about the Dunkirk cluster was collected via an LESTS survey and an interview. Following is a synthesis of the primary data that were collected through the survey and the interview and the secondary data that are published on the industrial symbiosis in Dunkirk.

3.5.1.1 Social

The port of Dunkirk has received attention from many authors for the cases of industrial symbiosis that are in place (Hampikian, 2017a, 2017b, 2017d, 2017c; Morales & Diemer, 2019; Pitkänen et al., 2016). Although the focus is directed to District Heating Network (DHN) and the symbiosis activities that have ArcelorMittal at their heart, a brief history of the Dunkirk cluster is worth mentioning.

Back in the sixties, many exchanges of flows between the private companies in Dunkirk were in place, owing to the economic reasons and technical constraints that pushed the companies to look for local solutions. When the public authorities showed commitment to the Local Agenda 21, more initiatives were put in place to combat the economic and environmental challenges that followed the economic crisis of the seventies. With the start of the DHN, public authorities also got involved in the symbiotic activities. These initiatives inspired the private businesses to start a 'club' of sorts with thirty members, who were engaged in gas exchanges.

Industrial symbioses in Dunkirk have emerged as a conscious effort by the city of Grande Synthe and several companies located in the industrial area of Deux Synthe, ArcelorMittal, Ascométal, and ENGIE (GDF before), who got together in 1999 to study the potential of the region to develop an industrial ecology vision. In 2001, with explicit commitment to industrial ecology principles, EcoPal (a non-profit organisation) was created. Now the association managed by EcoPal has more than 200 members, including big firms, SMEs, local institutions and associations. All the members share the same view of supporting local sustainable development in the area.

In the following section, first, a brief introduction of the different stakeholders in Dunkirk industrial cluster is provided and then a historical account of the cooperative activities that led to the development and extension of the DHN are outlined.

Dunkirk Urban Community

Dunkirk Urban Community (*Communauté Urbaine de Dunkerque - CUD*) was created in 1968. It was a community of 12 towns when it officially began to operate in 1969. Since the nineties, CUD has successfully implemented an industrial policy aimed at supporting economic development, which focuses on environmental protection and improvement of quality of life. In 2019, it is composed of 21 towns and villages that cover a part of Flandre Maritime and all the coastlines of Northern France. CUD also represents the community in negotiations with the state and the region.

The three missions of CUD include:

- **The organisation of major public services** (waste, sanitation, transportation, roads, etc.) that fall within the legal tasks of CUD and that are developed either directly or through funds of the participatory municipalities.
- **The development of the region** through development policy partnership, which does not stem directly from the historical skills but are essential to the development of the town.
- **The guarantee of a regional cohesion.** CUD is in charge of the development of a cohesive vision for the development of the region. Strategies that fall under this vision are divided into four sectors; the climate plan, the local plan of urban habitat and inter-community urban transport plan, and waste collection.

CUD has a strong focus on power industry and the potential gains owing to the multitude of major power producers, importers, consumers and processing facilities based in Dunkirk (nuclear power station, DK6, biofuels, wind farm, energy recovery centre, district heating system, methane terminal and gas pipeline terminus, coal port, etc.).

CUD collaborated with Nord-Pas de Calais to establish the **Energie 2020** centre of excellence. This cluster aims to support power industry companies both in economic and in energy transition. Particular areas of focus include the development of hydrogen and the recovery of waste heat in conjunction with Ecopal, the analysis of storage and the development of the biomass and renewable energy sectors.

The Dunkirk area is also leading the way by piloting the **Windustry cluster**, which aims to develop the regional offshore wind industry. This follows the emergence of the French power, transport, and storage sectors. Dunkirk is also home to the **GRHYD** project (injecting hydrogen into natural gas), which has secured investment for the future and demonstrates the economic credibility of the hydrogen sector (*The GRHYD Demonstration Project | GDF SUEZ*, n.d.).

CUD heads the management of the DHN.

ArcelorMittal

Located in the North of France, the port of Dunkirk has a long history in iron and steel works for more than 50 years. Today, the ArcelorMittal Dunkirk site is one of the five largest sites in Europe. Built in 1963, the ArcelorMittal steel works is specialised in the production of flat carbon steel. At Dunkirk ArcelorMittal holds France's largest steel mill, which accounts for approximately 1.5% of the country's total energy consumption (Dujardin, 2009). As highly energy-intensive industry, ArcelorMittal joined forces with the CUD to feed the city's district heating network, built in 1985. ArcelorMittal Dunkirk has strong social embeddedness in Dunkirk district cluster due to their presence in the cluster for a long time and their active contribution to the development projects in the region. ArcelorMittal also participates in a number of environmental and regional development programmes with CUD.

Although EcoPal provides the services of an industrial symbiosis facilitator and manager in the Dunkirk region, ArcelorMittal does not use the services of EcoPal to manage its symbiotic flows. The reason is that the flows from ArcelorMittal are of such huge quantities that it makes better economic sense to manage them internally.

ArcelorMittal provides 60% of the heat for the DHN.

Dalkia-EGL (Energie Grande Littoral)

In 1985, the concession for operating the DHN was awarded to Compagnie Générale de Chauffe, which was then bought by Compagnie Générale des Eaux. Compagnie Générale des Eaux later became Veolia. Dalkia is now completely owned by EDF. In 2001, Dalkia-EGL, a subsidiary of Dalkia was created to solely take over the operations of the Dunkirk DHN.

Customers

Today, the heat network not only heats the city hall, a hospital center, a swimming pool and schools, but also the equivalent of 16,000 social housing units ('Collaborer Avec Des Industriels', n.d.).

Ecopal

Ecopal is a non-profit organisation supported by companies and public actors in Dunkirk. It accompanies and provides services to member companies, focusing its work on the implementation of circular economy and industrial ecology, to lead them to new environmental economic models. Ecopal was created in 2001 by 17 companies in the Dunkirk region, with the objective to support its members in the concrete application of industrial ecology while allowing them to focus on their core business. Ecopal is working on four major themes: water, biodiversity, waste, and energy. ArcelorMittal is part of the administrative council of Ecopal. This administrative council is responsible for taking strategic decisions on waste and energy projects.

Grand Port Maritime de Dunkerque

Grand Port Maritime de Dunkerque (GPMD) manages the port and the surrounding region of port of Dunkirk. GPMD is also committed to the goal of overall improvement in the regional impact on environment and society. GPMD also communicates regularly with ArcelorMittal and CUD to develop the area by particularly involving organizations and industries.

The history of Dunkirk DHN can be traced back to the oil crises of 1973 and 1979, when the cities of Dunkirk and Saint Pol sur Mer needed to find an alternative to fossil fuels. In 1983, they formed a union, called the SICURD (Syndicat intercommunal district heating of the Dunkerque region). SICURD decided to build a heating network that would be supplied primarily by recovered by-product heat from a local industrial process. A techno-economic feasibility study of a DHN that would be mainly provided with waste heat from Usinor plant was carried out. Following a nationwide request for proposals, CUD, chose Company Générale de Chauffe (renamed Dalkia) as the concession holder to build and operate the network. Based on the feasibility study Usinor (now ArcelorMittal) was easily convinced to provide the waste heat. The social aspect of personal relationships between the then Mayor of Dunkirk, also the president of SICURD and the people at Usinor. Construction of the heating network began in early May 1985.

A capture hood was used to recover heat at the Usinor steel works in early 1986. By 1990, the heating network was already supplying 120 substations (customers). The first service concession arrangement was signed on 24 April 1985 for an initial period of 24 years. In January 1992, an amendment to the arrangement extended the contract through 30 June 2024, enabling the initial project costs to be repaid over a longer period.

In 2001, a new amendment transferred the service concession arrangement to Dalkia-EGL. Changes in the arrangement led to upgrades in the production facilities and the distribution network, in particular to recover heat produced by the ArcelorMittal plant.

3.5.1.2 Legal

After the crisis of 1970s, the public authorities tried to support the failing steel sector in France. Under the same scheme, state became the majority shareholder. In 1982 Usinor was nationalised and later in 1986, a new merger at the national scale give birth to Usinor-Sacilor. Only in 1995, when the steel crisis was over that the state returned the business to private parties (Hampikian, 2017a). This legal history of ArcelorMittal is interesting to understand the ease between the different partners at the time of inception of the DHN. Legal difficulties began to emerge when the different organisational structures grew apart, i.e. the legal contracts were now between public and private partners. The control that the local actors had over the steel industry was significantly diminished when Indian Mittal Steel Company took over the company in 2006.

In 1985, there were three adjacent communes to be involved in the emergence of the network: Dunkerque, Saint-Pol-sur-Mer, and Grande-Synthe. The three communes joined forces to construct and develop the DHN. However, Grande-Synth left the group as there were no plans to extend the DHN to the commune of Grand-Synthe. Later, the two communes merged in 2011 and the DHN was managed by the city of Dunkirk. The administration of the network was carried out by the energy department of the city. Later, in 2014, the management of the DHN was transferred to CUD. CUD is still responsible for the DHN and now holds the granting authority of the management of the network.

The legal evolution of Dalkia from Compagnie Générale de Chauffe did not have significant effect on its role of DHN operator. Dalkia is completely owned by EDF. In 2001, Dalkia-EGL, a subsidiary of Dalkia was created to solely took over the operations of the Dunkirk DHN.

ArcelorMittal Dunkirk regularly collaborates with CUD on the matters of DHN. This collaboration follows the classic business relationship between a company and a customer, the provider being ArcelorMittal and CUD being the customer. Dalkia in turn has a concession from CUD to operate the network.

In 2006, the network was expanded and a new capture hood was proposed to be installed on the sinter plant no. 3 of ArcelorMittal. This time, ArcelorMittal agreed to contribute to the cost of the installation given that the capture hood will also capture the dust emissions. The dust emissions are monitored by the Regional Directorate for the Environment, Planning and Housing. This regulatory push helped to realise the network expansion which might otherwise be hampered as the network operator Dalkia-EGL could not afford the full investment (Hampikian, 2017c).

There is no legal obligation by CUD for the new buildings to be connected to the DHN, also there is no market protection for the DHN. This increases the risk for Dalkia. Due to the difference in interest between CUD and Dalkia, Dalkia has refused to extend the network due to many uncertainties that risk future operations of the DHN (Hampikian, 2017c).

3.5.1.3 Economic

Though it may appear that the benefits of providing heat for free to the DHN are not very high in terms of economic gains but these impacts contribute to better business relationships, positive impact on the environment and better quality of life of the surrounding community.

It was reported in the LESTS survey that DHN does not contribute to ETS credits for ArcelorMittal in 2015. In the legal agreement between Dalkia-EGL and ArcelorMittal, the ETS credits will be shared between the two partners if the carbon price goes above 15 euros/ton of CO_2 (Hampikian, 2017a). Since 2015, the carbon price has increased, however, the new information regarding this point was not shared during the LESTS survey.

The economic factors that influence the Dunkirk DHN are of diverse nature. First, the main provider of heat is the steel industry, hence the network is vulnerable to changes in the steel market. This was particularly felt during the 2008 crisis when the steel production was reduced and the DHN had to be fed by other heat sources. Second, the production schedules of ArcelorMittal dictate the heat supply of the DHN, which do not always coincide with the demand. The mismatch between supply and demand also causes extra tax burden on Dalkia-EGL. In France, 20% tax is paid on heat that has sources of more than 50% fossil fuels. However, if the fossil fuels account for less than 50% of the source, then the tax is reduced to only 5.5%. Dalkia-EGL has to declare the heat sources for the DHN every three months and this again increases the susceptibility of the profits from DHN due to main reliance on ArcelorMittal (Hampikian, 2017a). Third, the payback period of the DHN is long and risks of bankruptcy of the partners impacts the resilience of the DHN. Therefore, the public authorities in collaboration with Dalkia-EGL are trying to spread the risks by seeking more public partners of versatile nature to provide the needed heat. The new partner has been identified as the energy recovery centre.

It was reported in 2016 that there is a study underway for creating a guarantee fund provided by ADEME, as an assurance in case of loss of customer base or the cessation of heat supply from ArcelorMittal (Hampikian, 2017a).

3.5.1.4 Spatial

The feasibility study of Dunkirk DHN notably accounted for proximity between the heat source and the potential consumers (social housing and public buildings) (Hampikian, 2017c). Although the spatial proximity is a key factor in a DHN, other factors such as the organisational control that CUD can have on public sources of heat as compared to private companies has also played a role in rethinking the DHN. Since Dunkirk is a port city and has many other industrial and non-industrial sources of heat, CUD and Dalkia-EGL are seeking other local partners to spread the risk of supply.

3.5.1.5 Technical

In 1986, a large capture hood was installed on one of the cooling beds of sinter plant no 3. The capture hood was able to recover 20 MW of heat that was then provided for district heating at a temperature of around 110 ^oC. The sinter is initially at a temperature of 400 ^oC and needs to be cooled down before the heat can be captured at 110 ^oC. The reason for this lies in the total heating demand of the network, which is less than what ArcelorMittal can supply. Also, the supply of heat will be much more than the demand in warmer seasons if all the heat was captured. Additionally, the physical dimensioning of the sinter plant does not allow for a capture hood to cover the full surface, which will cause the hot sinter to be confined in a small space and may damage the bottom of the sinter plant. The capture hood only covers one-third of the sinter bed (Hampikian, 2017a).

In 2008, a new capture hood was installed on the cooling bed of sinter plant no 2. Now the capacity from ArcelorMittal has increased to 28 MW.

The heat recovered by Dalkia comes from air that is heated when it flows through the sinter coming off the cooling bed of the sinter plant that fuels the blast furnace. The principle of hot air capture is simple. A large hood placed over the cooling bed draws hot air through an exchanger where it heats water that is then distributed via the network. The average temperature of the water in the DHN is 110 ^oC.

Heat distribution is carried out entirely by a system of pre-insulated buried pipes. Initially, the heat recovery unit and the main Ile Jeanty heating plant were connected with water pipes made of welded steel tubes and the rest of the network was made of cast iron. Because these materials wore down quickly, also because new and more durable processes had been invented, the entire network was replaced with pre-insulated pipelines. Replacement began in the early 1990s and was completed in 2003. Today, network losses represent 10.4% of annual heat output.

3.5.2 LESTS Outcome

Symbiotic activities have contributed to the business attractiveness of the port of Dunkirk (Economic Development Agency, 2019). Although, it is reported that the synergies in Dunkirk have not always been profitable enough to attract investment (Pitkänen et al., 2016).

Based on the cluster dynamics that are enumerated in the last section, it can be deduced that the industrial symbiosis particular to the Dunkirk DHN has emerged as a result of the **facilitation - brokerage** by the public authorities. The public authorities created a market for the waste heat by installing the DHN infrastructure and connecting the industrial waste heat to the customers. The industrial symbiosis has then evolved to **facilitation – collective learning**, as the learning from DHN also contributed to the development of other exchanges.

Inventory of industrial symbiosis in Dunkirk shows that there are 26 flow exchanges between firms (81% material flows, 15% energy flows and 4% water flows), which contribute to significant environmental benefits (Pitkänen et al., 2016). These benefits include preserving natural resources, decreasing waste production, and reducing air emissions (i.e., 16 thousand tons of dust particles, 1.6 million tons of CO_2, 600 tons of NO_x, and 360 tons of SO_x are avoided annually) (Pitkänen et al., 2016). The use of recovery of industrial heat avoids use of 2500 tonnes of heavy fuel oil and emissions of 26,000 tonnes of CO_2 (Pitkänen et al., 2016).

Based on the environmental gains and the institutional evolution in the Dunkirk cluster, it shows the characteristics of **strong sustainability.** In Dunkirk, new community structures have emerged to steer the region towards economic sustainability (CUD) and promote industrial ecology related initiatives (EcoPal). The community-led initiatives have become the norm, as is apparent by the formation of EcoPal, the Energie2020 and Windustry. Integration of economic, social, and environment values is apparent in the vast number of symbiotic exchanges that are in place in Dunkirk, which result in the avoidance of primary materials being used and CO_2 emissions.

According to the three stages of industrial symbiosis, as defined by Chertow and Ehrenfield (2011), the Dunkirk cluster shows an advanced stage in the development as a complex system, where symbiosis has been **institutionalised and embedded** in the public-private and private-private partnerships in the region.

3.5.3 Symbiosis Opportunities

In the region of Dunkirk, ArcelorMittal is the only industry that participated in the case study. It was not possible to propose any symbiotic opportunities to ArcelorMittal since there was no other partner available.

CHAPTER 4. SWOT ANALYSES

In this chapter, the most relevant pieces of contextual information acquired from the LESTS assessment are used and the Strengths, Weaknesses, Opportunities, Threats (SWOT) of each of the cluster is provided (Hill & Westbrook, 1997). It provides some guidelines to draft sustainability goals of the cluster that might direct towards the implementation of further symbiotic networks (Baas & Boons, 2004b).

At the end of the LESTS assessment, industrial symbiosis opportunities were identified for each of the three industrial cluster. A SWOT analysis of the most promising industrial symbiosis is drawn to provide a qualitative grasp of the implementation potential of these industrial symbiosis opportunities. In addition, SWOT analyses of each opportunity can be carried out in order to refine the preliminary list of industrial symbiosis opportunities and prioritise them for furhter assessment.

Here, it is useful to reiterate that not all of the clusters had more than one industrial partners particiapating in the clusters. Hence, the identification of symbiotic activities and their respective SWOT analysis is only carried out for the cluster where there were more than one industrial site participating in the case study.

4.1 RUDNIKI (POLAND)

The Rudniki cluster has been assessed for the SWOTs and the result is provided in Table 4-1.

Table 4-1: SWOTs of the Rudniki cluster

Strengths	Weaknesses
Large and established industries	Geographical proximity is not optimum
All industries operate in stable markets	There are no existing social ties between the industries in Rudniki cluster
Opportunities	**Threats**
Possibility to collaborate via EPOS network	Stricter regulations on carbon emissions, increased circularity of materials/products
Availability of tax write-off and subsidies for energy efficiency improvement projects	Competitors from in- and outside of Europe
Wastes and by-products matches are technically possible between the different industry partners	

The data collection supplemented with the LESTS assessment helped to identify many symbiotic opportunities in the Rudniki cluster. Three of these opportunities were prioritised by the concerned industries to focus further. These opportunities are briefly described below. Some other opportunities were also proposed to the industries but were not deemed of high interest by the industries. These opportunities are provided in the *annex* (see Table A-3).

An example from the Cement Rudniki plant is quoted to emphasise how industries can independently contribute to low-carbon economy by providing demand side response for balancing the electricity grid.

4.1.1 Lime-meal from cement to minerals

Lime-meal (or simply limestone rich reject stream), as termed by Cement Rudniki, mainly consists of limestone. Cement Rudniki expressed a high interest to find a use of this product that cement uses as aggregate, with a blend of 88-94% limestone and about 6 to 12% of CKD. The annual production of the material is approximately 78 k tons. It was proposed to cement to sell this lime-meal to minerals, where it can be used in the production process.

4.1.1.1 Possible scenarios

Since Cement Rudniki lies next to the freight tracks that transport material between the two sites of minerals. The train going between Romanowo and Jasice could be used to bring this limestone rich reject stream from Cement plant to the Minerals site. In this way the extra capacity of the freight train can also be utilised.

4.1.1.2 SWOTs

Table 4-2: SWOTs of industrial symbiosis case - lime-meal from cement to minerals

Strength	Weakness
The industrial symbiosis is compatible with the core processes of both partners The material is easy to transport via truck or train No transport related emissions, as Cement Rudniki is situated between the two plants of Minerals that already have a train connection between them for material transport	Minerals has a quarry at Romanowo with excess raw material, hence the extra limestone from Cement does not bring a significant benefit to Minerals
Opportunities	**Threats**
The exchange between the two partners may result in sustained economic benefits for both partners	Industries in closer vicinity could become more attractive partners as the synergy is established and mature

Upon further inquiry it was discovered that the Minerals plant requires raw minerals to be of a certain grade of white colour. The lime-meal that is produced by Cement Rudniki does not meet that requirement. Also, given that Minerals already has an excess of raw material on their quarry, the symbiosis was not realised during the time of the case study.

4.1.2 Slag from Steel to Cement

Blast furnace (BF) slag from Steel can be sold directly to cement for clinker production. In this opportunity, it was proposed for the two industry partners to bypass the third party and engage in the industrial symbiosis directly.

The BF slag produced by Steel Krakow can be directly sold to Cement Rudniki for use in clinker production. BF slag mainly contains inorganic constituents such as silica (30–35%), calcium oxide (28–35%), magnesium oxide (1–6%), and Al_2O_3/Fe_2O_3 (18–25%). Due to the low iron content it can be safely used in the manufacture of cement (Das et al., 2007).

4.1.2.1 Possible scenarios

Since the synergy is already in place through the vendor, there is a possibility to improve the cooperation between the two partners in future. steel could fulfil the full requirement of slag from cement and possibly send Basic Oxygen Furnace (BOF) slag to cement for clinker production as well.

The trucks that bring slag from steel to cement could be used to bring back material from cement to steel, hence, optimising the logistics.

4.1.2.2 SWOTs

Table 4-3: SWOTs of industrial symbiosis case - slag from steel to cement

Strength	Weakness
The industrial symbiosis is compatible with the core processes of both partners	The quantity of the BF slag does not satisfy the full demand of cement
The material is easy to transport via truck	Emissions caused by transport of material dampen the environmental benefits of the industrial symbiosis
Opportunities	**Threats**
Further collaboration is possible, e.g., sending the metal scrap and plastic waste from cement to steel to be used as raw material, optimising the logistics	Since the demand of slag on the market is much higher than the supply from steel, there could be other buyers willing to pay more for the same material

As mentioned earlier in Chapter 3, the two parties have now engaged in direct contract of selling BF slag from Steel to Cement. The contract was finalised in December 2017 and will ensure that steel provides half of the slag requirement of cement. Since the quantity of BF slag is not very high, it is transported via trucks between the two partners. This also suggests that distance is perceived relative to the economic benefit of the symbiosis, hence the distance of 164 km is not a hurdle if both parties benefit from the symbiosis.

4.1.3 Scrap metal and waste plastics from Cement to Steel

Scrap metal from all the milling operations and demolished buildings at the site of Cement Rudniki can be sent to steel for recycling. Also, the plastic supplements from waste packaging can replace a small percentage of coke as a secondary raw material in the blast furnace of Steel plant. These waste streams are not prepared for direct use in another process hence they are sold to waste handling third. The quantity of both streams is not very large in magnitude. The scrap metal, mainly composed of iron and steel, has a magnitude of 5000 tons/year, with a varied particle size of 1 to 10 cm. The plastic and rubber waste is produced continually throughout the year and has an approximate quantity of 7 tons per year.

4.1.3.1 Possible scenarios

There can be a direct link between Cement and Steel or a waste handler, such as the engineering company, can provide the service of preparing the plastic and metal waste streams for the processes at steel plant. Since these waste materials are not specific to cement process, Minerals could also contribute to the same symbiosis. As suggested before, the trucks that bring slag from Steel to Cement could be used to transport these two material streams back to steel.

4.1.3.2 SWOTs

Table 4-4: SWOTs of industrial symbiosis case - scrap metal and waste plastic from cement to steel

Strength	Weakness
The material is easy to transport via truck The industrial symbiosis is simple to achieve	The quantity of the waste streams is not significantly high The synergy is not directly related to the optimisation of the core business of either of the industries
Opportunities	**Threats**
Possibility to bundle different synergies together to reduce costs and environmental burdens of transport	The conventional route of waste collection may prove more convenient for cement to not consider this synergy

Although this symbiotic activity is simple to achieve but none of the parties involved showed further interest and the symbiosis was not studied any further.

4.1.4 Individual case – Virtual Power Plant and cement

A Virtual Power Plant (VPP) is a network of decentralised, independent units that are engaged either medium sized energy producers or flexible energy consumers, who are engaged to relieve the load on the grid during peak hours. Since 2014, Cement Rudniki is part of a VPP, called Espirion. Espirion is a national initiative by the Polish government. If requested by the VPP, Cement has accepted to switch off some units that are connected to the VPP, during the daytime. During the night, Cement can keep its production processes running without any hindrance. Cement gets a fee from Espirion for being a part of the VPP and Cement also has the right to ask for a further fee, when asked to shut down the selected units. Cement Rudniki provides 6-12 MW of flexibility in electricity to the VPP.

The benefits of the VPP are enumerated as having low investment cost and being economically beneficial for the Cement plant. The Cement plant helps the local electricity network to avoid black outs through balancing energy on the grid. In countries where renewable energy is being injected in the electricity grid, such initiatives provide the electricity intensive industry to take on their ecological responsibility by providing flexibility in demand. Cement Rudniki also deems the VPP in helping a positive image of the company, as they now hold a Certificate for supporting Polish Energy Security.

This example proves that large industries can provide electrical flexibility and gain financial benefits for it. This case was communicated to other partners in the consortium as an option for all the industries to engage in virtual symbiotic networks with industries in their respective cluster. This example and one that will be explained under the Humber cluster formed the basis for Chapter 6 in this thesis, where a low carbon energy grid is imagined, and electrical flexibility of industries is tested for its suitability to ensure the grid balance.

4.2 LAVÉRA (FRANCE)

The Marseile-Fos industrial cluster holds many examples of industrial symbiosis and many initiatives that promote industrial symbiosis in the region. The French Cluster policy from 2005, extended till 2012, also points to the focus of policy makers to encourage industrial cluster formation for economic and ecological benefits (Fontagné et al., 2013). After the LESTS data were collected from the two industrial partners in the Lavéra cluster, the SWOTs were outlined and they provided in Table 4-5.

Table 4-5: SWOT list of Lavéra cluster

Strengths	Weaknesses
Large and established industries operating in stable markets Existing ties between chemicals and steel Presence of third parties willing to provide a platform for exploration of new symbioses Diverse industries agglomerated in a vicinity, hence many options for symbiosis exist even outside of the cluster	Established industry with large investments in infrastructure, which makes it harder to implement radical changes Geographical proximity is not optimum.
Opportunities	**Threats**
Possibility to collaborate with the Grand Port Mediterranean and seek (financial) support infrastructure to support industrial symbiosis	Both companies face competitors in- and outside of Europe

As a result of the LESTS assessment and SWOT analysis, many opportunities were identified, and the most promising symbiosis activities were further studied. Only two of these opportunities were shortlisted by the industries, which are discussed further in this section. A few other opportunities were also proposed but they did not incite interest from the industries. These opportunities are provided in the *annex* (see Table A-5). An example of an on-going activity at the steel Fos-sur-Mer plant is quoted as well to narrate how industries can individually contribute to low carbon economy in innovative ways.

4.2.1 Naphthalene gasoil from steel to chemicals

Gasoil is used to strip the gases from the oven at steel Fos-sur-Mer site. The spent gasoil, called naphthalene gasoil, has the similar properties as ordinary gasoil, which can be used as fuels in automobiles. The extra component naphthalene makes this gasoil less desirable to be burnt as it produces VOCs (Volatile Organic Compounds) on combustion. Steel uses flue gases (COG, BoG and BOFG) as main back-up fuel for the boiler but sometimes naphthalene gasoil is also used. Currently, the emissions from the combustion of this fuel do not cause a breach of emissions' regulations in France. However, Steel aims to improve their environmental profile and is striving for a replacement for this fuel. The highest point of concern for Steel is the particulate matter from the naphthalene gasoil. There is no existing market for naphthalene gasoil, hence Chemicals could be a potential buyer of this fuel. In return Chemicals can provide a cheaper spare fuel from their refinery, in exchange for the naphthalene gasoil. The naphthalene gasoil from Steel is a high-quality fuel with an estimated worth of 1000 euros per ton. However, the amount 5000 tons / year is not a significant magnitude to look for economically viable investments in new technology to clean the waste fuel at Steel Fos-sur-Mer site. Hence, this symbiosis sparked interest from both companies.

4.2.1.1 Possible scenarios

Possibility 1: Chemicals can buy the naphthalene gasoil from steel in exchange for a cheaper fuel (worth approx. 500 euros/ton), which will replace the use of backup fuel at steel. Chemicals can use the naphthalene gasoil in their processing unit, by blending it with crude oil and separating the impurities from gasoil.

Possibility 2: Chemicals can provide a service to steel by taking the naphthalene gasoil and separating the aromatic compounds from the gasoil and providing the clean fuel to steel to use for stripping the exhaust gases. Thus, reusing the gasoil over many cycles of produced. Chemicals can ask for a price comparable to the price of gasoil for this service. In that case, Steel will need to look for another source of lower quality fuel to use as backup fuel.

4.2.1.2 SWOT analysis

Table 4-6: SWOT analysis of industrial symbiosis case - naphthalene gasoil from steel to chemicals

Strength	Weakness
The industrial symbiosis is compatible with the core processes of both partners	The quantity of the naphthalene gasoil is not significant for either party
The material is easy to transport via truck Investment costs are minimal for both partners	Emissions caused by transport of material could reduce the environmental benefits of the industrial symbiosis
Opportunities	**Threats**
Economically beneficial for both parties Can pave way for further collaboration	It may take time to acquire permits to transport naphthalene gasoil via truck A market for naphthalene gasoil can result in diverting the flow from Chemicals, hence ending the industrial symbiosis

Till the end of the case study, the two companies were assessing the case. After the NDAs were signed the testing of the naphthalene gasoil was carried out in the labs at the Chemicals' site to check the suitability of the fuel to be used in the refinery.

4.2.2 Coke from Chemicals sent to Steel

Coke is produced from steam cracker on Chemical's site. Currently, the engineering company manages this by-product of Chemicals. Since Steel requires coke in their sinter plant, the coke produced at chemicals can be sold to steel, given that the characteristics are acceptable to be used in the blast furnace of Steel. The quantity of coke produced at Chemicals is approx. 260 t in 1.5 year.

4.2.2.1 Possible scenarios

The only possible scenario for this industrial symbiosis is to sell the by-product from Chemicals to Steel and arrange the transport via trucks.

4.2.2.2 SWOTs

Table 4-7: SWOT analysis of industrial symbiosis case - coke from chemicals to steel

Strength	Weakness
The industrial symbiosis is compatible with the core processes of both partners The material is easy to transport via truck Investment costs are calculated to be minimal	The quantity of the coke is not significantly high to fulfil the requirement of Steel Emissions caused by transport of material
Opportunities	**Threats**
Could prove economically beneficial for both parties Can pave way for further collaboration	Conventional suppliers of coke can easily replace the Chemicals company as the supplier of coke for Steel Ending the contract with the engineering company may strain the business relation between the engineering industry and, Chemicals and Steel

Coke produced at the Steel site holds the status of a 'waste' stream. This status has to be changed prior to any reuse and thus symbiosis. The legal costs and time required for this change of status (including policy amendments), along with the low quantity and variable quality of the stream shows high transactional costs for this symbiosis.

When the last information was collected from the industry, the symbiosis was still being appraised but not yet realised.

4.2.3 Individual case - Solar panels on Steel Fos-sur-Mer site

At the steel site in Fos-sur-Mer, the EDF Energies Nouvelles installed 12 MW solar panels on the land owned by the Steel company. The land has to be leased for at least 20 years, according to French law. Equipped with over 45,000 photovoltaic panels, the 12 MW solar plant generates the equivalent of the annual electricity consumption of 7,400 inhabitants, which represents half of the Fos-sur-Mer population. Steel gains no clean electricity or green credits or certification from this activity.

This activity can be replicated on the site of Chemicals, with some improvements. Chemicals site can benefit from the collaboration and use the electricity on their site. It is encouraging that Chemicals has already made some cost estimates for the installation of solar panels on their site and now can learn from the experience of Steel.

4.3 HUMBER (UNITED KINGDOM)

The Humber cluster of provided the most interesting results that also formed a part of a publication that the author contributed to (Cervo et al., 2019). In this part of the chapter, the SWOTs of the Humber cluster are provided in Table 4-8.

Table 4-8: SWOT list of Humber cluster

Strengths	Weaknesses
Established industries with long history of embeddedness in the local industry and community Active participation in the local initiatives for policy recommendation Expressed willingness to collaborate Availability of investment capital	High dependence on non-renewable energy Established industry with large investments in infrastructure, which makes it harder to implement radical innovations Currently the volumes of sharable streams for industry symbioses are not high enough to incite interest by the partners Geographical proximity is not optimum for joint site management options
Opportunities	**Threats**
Waste valuation and exchange between the industry partners District heating between Cement and the South Ferriby community Waste streams from chemicals used as fuel in cement Renewable energy production options, e.g., wind turbines and micro-hydro turbines	Stricter regulations on carbon emissions Stricter regulations on permissible particulate matter emissions Stricter regulations for increased energy efficiency Competition in- and outside UK Uncertain implications of Brexit

A number of symbiotic opportunities were proposed to the industries in the Humber cluster, however only two were studied extensively as part of the case study. These two opportunities are discussed in this section. The other opportunities are provided in the *annex* (see Table A-7).

An example of a ceased attempt at installation of wind turbines by one of the partners in Hull is quoted to point towards the non-technological and macro-level effects that may result in discouraging industries to invest in projects for low carbon energy.

4.3.1 PLF stream from chemicals to cement

From the list of symbiosis opportunities proposed in Chapter 3, the opportunity involving the Primary Liquid Fuel (PLF) has the highest score. This opportunity concerns the possibility for chemicals to send one of its liquid waste fuels to the cement producer and use it as alternative fuel. The stream from the chemical process is currently sent to a third party in exchange for steam. However, the PLF negatively affects the efficiency of the third party's boilers, thus the chemical company has to pay an extra price on the steam it receives. On the other hand, the cement producer has a permit to burn 100% alternative fuel (AF) in its kilns, and currently, due to limited supply, only 80% of the fuels burned are classified as AF. Since the PLF stream fulfils the primary specifications to be used as fuel inside a cement kiln (e.g., low heating value above 16 MJ/kg, and no contaminants under the form of heavy metals such as lead or mercury), it could replace a portion of the remaining 20% that is now provided by primary fuel.

The PLF stream from chemicals is currently handled by the engineering company, hence changing the current route of the PLF stream will affect the contract between chemicals and the engineering company.

This exchange depends on a number of qualitative and quantitative criteria. Both industries had to engage in detailed information exchange to investigate the feasibility of this industrial symbiosis. The two companies have signed NDAs between them and hence shared detailed information regarding the realisation of the symbiosis. Since chemicals Hull has an expansion plan, which will increase their production of EtAc by 40%, this increase can increase the PLF produced at the moment.

4.3.1.1 Possible scenarios

Ethylene Acetate (EtAc) production of the Chemicals company in Hull is expected to increase by 40%. This change resulted in two business scenarios being proposed to chemicals and cement. They are briefly introduced below:

Scenario 1: In the first scenario, the PLF stream is treated at Chemicals Hull site and is separated into two an acid fraction and an organic fraction. The acid fraction is recycled within the chemical plant and the organic fraction is sent to Cement South Ferriby. In this way, the PLF stream feeds 1.4% of the fuel use at cement plant. This scenario was most desired by the Cement company.

Scenario 2: In scenario 2, the expansion of the Ethylene Acetate plant is taken into account. Hence, there will be a larger amount of the PLF stream that could be sent to Cement, without prior separation into two fractions. Understandably, this scenario was not favoured by Cement.

Upon further investigation, it was found that splitting the stream into acid and organic fraction is also more economical for Chemicals. As the capacity of the plant increases, the volume of the PLF stream will increase. Not to mention that the demand for acetic acid will linearly increase as well. Once Chemicals took into account the possibility to send the organic fraction to Cement, the separation process of the PLF stream opened the new door to recycling of acetic acid. This proves that exploration of industrial symbioses can result in spill over effects and challenge the industries to think of options they were not aware of.

4.3.1.2 SWOT analysis

The SWOTs of this synergy are provided in Table 4-9.

Table 4-9: SWOT analysis of industrial symbiosis case - PLF stream from chemicals to cement

Strength	Weakness
A relatively simple industrial symbiosis No extra permits required Strong evidence of economic benefit for both parties The synergy is compatible with the core processes of both businesses	The PLF stream is produced in very limited quantity Any new installations to realise this synergy will need a capex that is taken from the core business, hence resulting in a difficult decision for the businesses Changing the contract between the engineering company and Chemicals may negatively affect their business relation
Opportunities	**Threats**
Improved environmental performance of both parties; Chemical company will gain cleaner steam as the boiler of the third party will run on a better efficiency using natural gas, and Cement will reduce the reliance on primary fuels	There is no surety that the fuel used by the third party to produce steam, will be less harmful to the environment or will reduce the cost of steam for chemicals A supplier of residue derived fuel can easily replace Chemicals' PLF stream by offering to fulfil the complete fuel requirement of cement

At the end of the case study, the two industries were still interested in the symbiosis and were engaged in sharing information regarding the further steps for realising the opportunity.

4.3.2 CKD from cement in exchange for Welton chalk stream from minerals

Cement South Ferriby produces 30,000 tons of Cement Kiln Dust (CKD) every year, it was proposed that this CKD load could be sent to the quarry site of Minerals for the purpose of land reclamation. Though the monetary benefits of this synergy are very attractive for both parties, and especially for Cement, a legal hindrance stops the companies from moving any further.

The possible scenarios and the SWOTs of the symbiosis opportunity are provided below that helped to lead to the conclusion that the symbiosis was not a suitable one.

4.3.2.1 Possible scenarios

Scenario 1: Cement can buy Welton chalk that is produced at Minerals. However, Cement has shown less interest in buying this stream, due to the presence of flint.

Scenario 2: Cement can send CKD to Minerals for land reclamation. However, this proposal is against the company policy of Minerals and also poses major environmental hazards for the quarry and the nearby community.

4.3.2.2 SWOT analysis

Table 4-10: SWOT analysis of industrial symbiosis case - CKD and limestone exchange between cement and minerals

Strength	Weakness
Cement can gain significant financial benefits if the CKD could be diverted from landfill Cement could extend the lifetime of their quarry or may avoid developing a new quarry (if chalk is exchanged)	CKD can cause serious groundwater pollution and needs careful management, making it inappropriate for quarry land reclamation The presence of flint in the Welton chalk is not appropriate for the processes at cement
Opportunities	**Threats**
The same transport trucks could transport the two materials between the parties, since CKD residues on the Welton chalk would not create a quality issue for Cement	Melton quarry and plant are located in a high groundwater vulnerability area, it is very unlikely that the authorities would allow for CKD disposal even with engineering protections in place

The SWOTs showed that a prohibitive regulatory aspect prevents the use of CKD in the old quarries of the mineral producer. Indeed, the CKD contains alkaline compounds that inhibit minerals from storing it in its career, as it is located in a flood-risk area. Therefore, costly infrastructures would be required to safely store the waste. The opportunity to re-use calcium carbonate rich reject stream also presents some weaknesses due to the composition of the chalk. Specific equipment would be required to sort the calcium carbonate reach stream, which would induce an additional investment that is too high compared to the low volume of the stream.

Considering all the qualitative and legal hurdles in realising this opportunity, there was no further investigation of carried out for this symbiosis.

4.3.3 Individual case – wind turbines at minerals Melton

During the data gathering process in the first year of the case study, it was found that Minerals and a neighbouring third party had received the permit to install five wind turbines on the land owned by Minerals and the third party. However, with the change of the feed-in tariff scheme of UK, the partners decided to only install three turbines. The economic incentives for connecting renewable energy producers to the grid further deteriorated. Although the other companies in the cluster showed interest and wanted to be fed clean energy, it was difficult for them to connect to the wind turbines through a direct cable. A direct cable to the wind turbines would require a heavy investment and lengthy legal procedures to get a permit for installation of a cable through privately owned land. If the companies share the clean energy via the grid, then there are no financial gains left for any of the partners. Since, Minerals will have to pay for using the grid and the other companies will also need to pay a fee to use the grid.

Also, there is no legal mechanism in place in UK that ensures that the existing network of cables could be used for connecting to clean energy producers and benefits or ETS credits could be claimed by the clean energy users. Final economic assessment shows that there is marginal benefit and management of Minerals has not committed to realising the project.

During the interview with Cement South Ferriby, it was gathered that there was also a proposal by Cement to install wind turbines close to their plant. The project did not materialise because of community's opposition. The main concerns from community are aesthetic and reduction in the value of real estate.

4.4 VISP DISTRICT HEATING AND COOLING NETWORK (SWITZERLAND)

The example Visp DH&CN provides an example of a strong anchor industry that provides employment to the large portion of the local community and is the source of heating and cooling network in the region. The SWOTs of the Visp cluster, which consists of the biotechnology company and the city of Visp is provided in Table 4-11.

Table 4-11: SWOT analysis of Visp Cluster

Strengths	Weaknesses
Spatial proximity between the community and industrial site is optimum for symbiosis Strong social embeddedness of the biotechnology company in the local area due to its position as a major job provider	No other industries in the immediate vicinity for further symbiosis Local bodies have a higher risk of being influenced due to the presence of single large industry
Opportunities	**Threats**
Plenty of space for new entrants to locate closer to the industrial plant and engage in businesses built around symbiosis with the company	Change in the pharmaceuticals market, i.e. stricter regulations on exports or lenient regulations on imports can influence the operations of the company

Table 4-12 provides the SWOT analysis of the Visp DH&CN.

Table 4-12: SWOT analysis of industrial symbiosis case – District heating and cooling network in Visp

Strengths	Weaknesses
Spatial proximity between the community and industrial site is optimum for a DH&CN Obligation to connect to the DH&CN ensures long term demand Technically advanced heating and cooling network	Extension of network is difficult as the valley is surrounded by mountains Price of power in Valais, especially hydropower, is extremely low Absence of financial reserves for Fernwärme Visp No other sources of heat and cold are present to spread the risks
Opportunities	**Threats**
Create a joint security fund between the company and the city of Visp	Stricter regulation of building standards (resulting in improved insulation of houses and less heating requirement); Unexpected large costs due to major technological repair, etc.

4.5 DUNKIRK DISTRICT HEATING NETWORK (FRANCE)

The long history of public-private symbiosis in Dunkirk cluster has been described thoroughly in Chapter 3 and the DHN is a result of this longstanding relationship. Based on the LESTS assessment, the SWOTs of the Dunkirk cluster provided below in Table 4-13.

Table 4-13: SWOTs of the Dunkirk cluster

Strengths	Weaknesses
Spatial agglomeration and optimum proximity for symbioses; Strong culture industrial symbiosis Improved image of the industrial area Stable leadership by CUD Presence of symbiosis facilitator (EcoPal)	Lack of certainty of long-term operation of private businesses Win-win solutions not always profitable enough Decreasing focus on local agenda by ArcelorMittal (after becoming part of multinational company)
Opportunities	**Threats**
Presence of intermediaries for initiation of industrial symbiosis; Huge source of untapped waste heat at ArcelorMittal can be used for other symbioses	Bankruptcy of private partners in the cluster Slump in economic activities due to global economic changes Relocation of industries to more attractive locations for business outside of Europe

The Dunkirk DHN provides a perfect example of the embeddedness of industrial and urban development in a region. The number of linkages between the different entities in the Dunkirk cluster increases the complexity of the network, however it also adds to the resilience of the system (Mat et al., 2017). One of these symbioses activities is the DHN in Dunkirk. The SWOTs of the Dunkirk DHN are provided in Table 4-14.

Table 4-14: SWOT analysis of industrial symbiosis case – District heating network in Dunkirk

Strengths	Weaknesses
Liability distribution made easy due to strong bond of trust Symbioses between actors formalized by contracts Security fund for the DHN provided by ADEME	Lack of certainty of long term operation of private businesses Diminished focus on local agenda by ArcelorMittal (after becoming part of multi-national company) Reduced influence of local public authorities on ArcelorMittal relating to the heating network
Opportunities	**Threats**
Extension of the DHN to neighbouring communities	Slump in the steel market A competing district heating network can be setup Cheaper stand-alone heating options for individual customers can enter the market

CONCLUDING CASE STUDY-I

The lack of spatial proximity and diversity of actors in the other three industrial clusters (Rudniki, Lavera, and Hull) proved to be a challenge from the very start of the case study. It is indeed true that process industries have a high potential to contribute to a resource-efficient and low-carbon future owing to their size. However, if the members of a case study for industrial symbiosis are only a handful of industrial sectors that have limited by-product streams and similar energy demands (heating and electricity), there is little chance to find symbioses opportunities between them. The process industries that partnered in the case study enjoy stable markets and have the margin to innovate in secure niches, but the spatial and technical limitations imposed by the combination of the sectors hindered the possibility to identify novel symbiotic possibilities. The limitations imposed by the confidentiality agreements also stalled deeper exploration of the cases for academic purposes. (Siskos & N. Van Wassenhove, 2016)

Related to the observations mentioned above, an insight for the industrial symbiosis facilitators needs to be mentioned. The industrial symbiosis facilitators are third parties or persons, who are responsible for identifying and managing the symbioses between the partners. Facilitators find it hard to create value for their business after the industrial symbiosis has been identified. One study points to the possible value creation for a synergy manager by taking on the responsibility to install the infrastructure for managing the symbiosis and hence ensuing a vital position in the symbiosis (Siskos & N. Van Wassenhove, 2016). Other models for facilitators are found in publicly funded programs, such as International Synergies as part of the NISP UK (International Synergies, n.d.). Since the H2020 programme funded the research, the role of facilitation was taken up without such requisites.

The successful uptake of industrial symbiosis by industries brings the discussion to the point of barriers of industrial symbiosis. The barriers to industrial symbiosis have been numerated by many authors (Golev et al., 2014; R. Lombardi, 2017; Van Eetvelde, Delange, et al., 2005; Van Eetvelde et al., 2007). Summarised by Golev (2015) the barriers to industrial symbiosis are: lack of commitment to sustainable development, lack of information, difficulty in trust and cooperation between partners, technical infeasibility, uncertainty and inconvenience in regulatory compliance, lack of community awareness and lastly, the economic infeasibility (Golev et al., 2015). Some of these barriers need to be removed within the individual organisation while some may need to be removed between the organisations and still some are outside the bounds of the organisations; in which case, involvement of third parties to provide leverage and remove barriers is a common practice (Paquin & Howard-Grenville, 2012; Siskos & N. Van Wassenhove, 2016).

There are costs involved in removing these barriers and in literature from economics, these costs are comparable to transactional costs (Williamson, 1979). If industrial symbiosis is institutionalised; by removing policy and information gaps, supporting knowledge exchange, building platforms for resource matching, removing spatial and legal barriers in the path to resource efficiency via symbiosis, these costs can be minimised. Institutionalisation has already been discussed in Chapter 1, as the final stage of evolution of industrial symbiosis. This process of institutionalisation has been discussed in detail in the chapter by Wouter Spekkink on the development of symbiotic network in the Netherlands (Spekkink, 2015). The noteworthy lessons for reducing the transaction costs include building trust between partners through time and regular contact, which in turn reduces barrier to information sharing and moulds the pathway to sustainable industrial symbiosis.

For future symbiosis identification:

To conclude the case study and provide industries with valuable information for seeking industrial symbioses with sectors that were not part of the case-study, a generic approach was adopted. It focused on monetary valuation of the by-products or waste streams that the industries wanted to find a use for. These streams were termed 'sharable streams', to avoid any contradictions regarding their legal status for symbiosis. The valuation of sharable streams was harmonised for each sector to show the value per ton of product (for steel and cement industry) or per ton of raw material (for chemical and mineral industry). The unitary costs of product or raw material for each sector are provided in Table 4-15.

Table 4-15: total cost of unitary production for each sector (used as reference to harmonise the value of sharable streams)

Industrial plant	Production cost	Unit	Reference
Steel plant	540	€ / ton of steel	(Moya et al., 2016)
Chemical plant	370	€ / ton crude oil refined	(*UFIP - French Union Of Oil Industries*, n.d.)
Cement plant	48	€ / ton of cement	(Moya et al., 2016)
Minerals plant	70	€ / ton of raw material	(*Prices Up Slightly for Ground Calcium Carbonate*, n.d.)

The valuation of a sharable streams depends on the value of the material or function that it is substituting. In Table 4-16 (on the next page) the economic values (opportunity cost) of the sharable streams from the four industrial sectors are provided. The fifth sector, engineering did not fit the criterion for this type of valuation, since they do not produce products but focus more on providing services to other businesses.

The list of streams is limited to the ones that were prioritised as the ones with highest level of interest for sharing by the respective industries.

Table 4-16: sharable streams and their unitary value

Sharable streams	**Can replace**	**Size of the stream (bulk)**	**Unit**	**Specific cost of the stream**	**Unit**
Steel					
BFG[1] (N, CO_2)	Heat source	-	Nm^3/yr.	0.76	€/ton of steel
BOFG/BOG[2] (CO 50%, CO_2 15%)	Heat source	-	Nm^3/yr.	0.87	
COG[3] (CH_4 H_2)	Heat source	-	Nm^3/yr.	0.69	
Tar	Primary fuel	-	t/yr.	2.57	
Naphthalene gasoil	Primary fuel	-	t/yr.	0.06	
Electricity	Electricity	-	kWh/yr.	1.29	
Metal Slag	Primary raw material	-	t/yr.	9.43	
CO tar	Primary raw material	-	t/yr.	1.57	
Chemicals					
Gasoline with sodium	Primary Fuel	-	t/yr.	0.42	€/ton of crude oil
CO_2 (in solution sent to 3rd party)	Primary raw material	-	t/yr.	0.002	
Residual gas	Primary fuel	-	t/yr.	0.63	
Hydrogen	Primary fuel	-	t/yr.	0.50	
LP[4] steam in excess	Heat source	-	t/yr.	0.12	
Cement					
Limestone quarry overburden	primary raw material	-	t/yr.	0.83	€/ton of cement
Scrap metal	primary raw material	-	t/yr.	0.83	
Water	primary raw material	-	t/yr.	1.17	
Gas (CO_2 rich streams)	primary raw material	-	Nm^3/yr.	1.59	
Exhaust gas	Heat source	-	Nm^3/yr.	1.25	
Minerals					
Chalk	primary raw materials	-	t/yr.	0.63	€/ton of minerals
Exhaust gas	Heat source	-	Nm^3/yr.	0.63	

BFG[1] – Blast Furnace Gas, BOFG/BOG[2] – Basic Oxygen Furnace Gas / Basic Oxygen Gas , COG[3] : Coke Oven Gas, LP[4] – Liquid Petrol

As an additional insight, the value of shareable streams per sector as heat, fuel or materials is summarised in Figure 4-1.

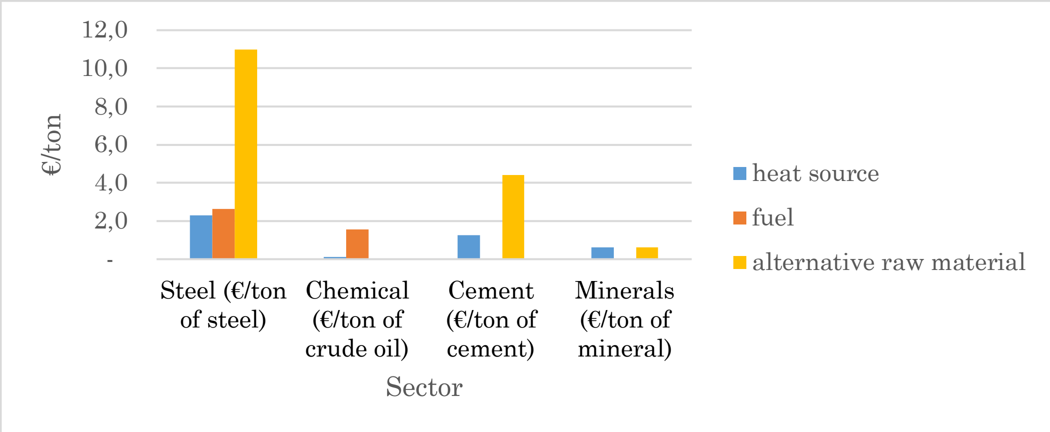


Figure 4-1: Bulk value of the shareable streams for each sector divided by the intended use

The steel sector is identified with the highest number of sharable streams and it has the highest potential value to be shared per unit of production. Overall, the streams that can replace a primary raw material have the highest monetary value.

This case study shows the potential for symbiosis between the process industries and gives an insight into the untapped potential in each of the four sectors; chemicals, steel, cement, and minerals. Outside of these sectors, finding symbiosis opportunities to valorise the sharable streams will not only provide monetary benefits to the industry but may improve the environmental benefits and overall societal well-being.

CHAPTER 5. METHODOLOGY – PART II

If during the later stages of industrial symbiosis feasibility study some barriers are identified that are caused by the existing policy regimes and cannot be removed unless system level changes are carried out; the stakeholders may abandon the symbiosis. One such barrier was also identified during the case study, relating to the unfavourable feed-in mechanisms for renewable energy. This led to the study of the (macro) factors at the system level that will bring about a system transition.

The symbiosis case in point relates to a company who wished to install five wind turbines in collaboration with a neighbouring company. However, the non-technical barriers relating to the changing subsidy scheme, the unfavourable grid connectivity costs and the change of focus of the regional plans led to postponing the symbiosis activity. This triggered the interest to study the non-technical aspects of the electricity grid and electricity markets at a broader system level. The connection between the system-level effects and the methodology for industrial symbiosis identification is presented in Figure 5-1 on the next page.

A hypothetical electricity grid was modelled with the help of agent-based modelling technique and different levels of feed-in tariffs for the wind farm owners were modelled in combination with increasing the installed capacity of wind power generation. To balance the grid and reduce the electricity market prices, the industries were modelled to provide demand side response. 5500 simulations were carried out to test which system-level factors could effectively help the current electricity grid to transition to renewable energy.

In this chapter the methodology to develop the agent-based model is presented. The methodology for the model is elaborated using the ODD + D (Overview, Design concepts, Details + human Decision-making) protocol (Grimm et al., 2010).

5.1 MODEL FORMULATION

Netlogo (6.0.2, Northwestern University, Evanston, IL, USA) (Wilensky, 1999) was used for modelling the electricity markets. ODD + D protocol is followed to ensure comprehensiveness when reporting models as it ensures that the description of the main theories and underlying assumptions in the model are clearly explained (Grimm et al., 2006, 2010).

5.1.1 Purpose

The model has been designed for generating data to quantify the effect of feed-in tariffs, installed capacity of wind power generation and demand flexibility from industries on the inclusion of renewable power in the grid and lowered market prices.

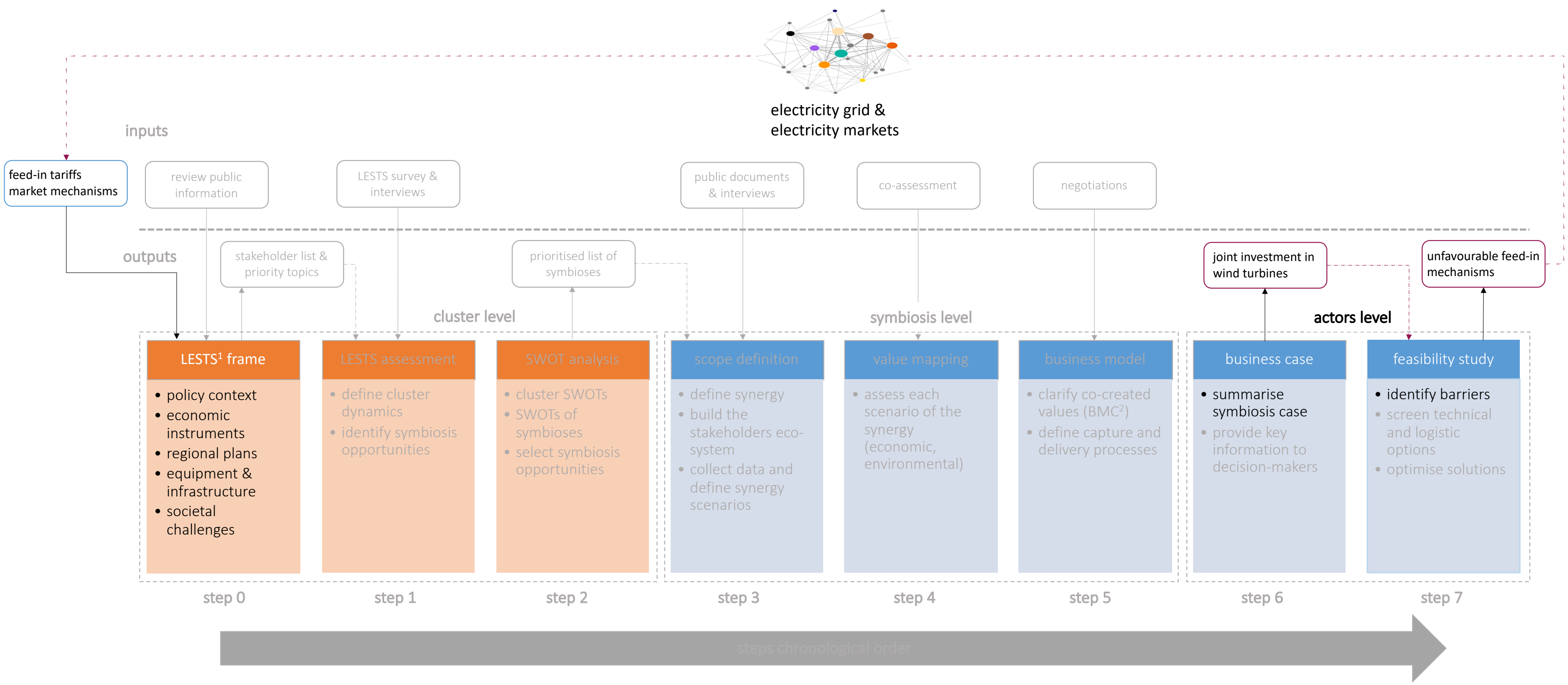


Figure 5-1. The connection of electricity market study to the methodology of the industrial symbioses case study (adapted from (Stéphane Ogé et al., 2019))

5.1.2 Entities, State Variables and Scales

The electricity grid modelled in for this study consists of three main agent groups; the electricity producers that are the wind farms, the large electricity consumers that are the industries, and the Small and Medium sized Consumers (SMCs) that are the households and small businesses. All of the agents are connected to the grid, which is operated by a grid operator, who ensures that the grid frequency is kept stable by reducing the mismatch between the supply and demand to zero. This system needs an efficient information and communication technology support. However, the technical details of the smart grid are beyond the scope of this model.

The model runs with quarter hourly time steps over a period of one year. The electricity grid is modelled as a stand-alone system, where the connections to markets or production systems outside of the model do not exist. The system parameters and the state variables are provided in Table 5-1, on page # 96.

Literature supports that fewer actors providing flexibility increases the likelihood of power they can exercise in defining the market price (Borggrefe & Neuhoff, 2011). To avoid this, it was also assumed that the size or capacity of the actors does not limit their ability to participation in either of the two markets. The properties of the agents are further described in the section below.

1. Renewable energy producers (2 groups)

The large renewable energy producers are modelled as onshore wind farms, with each turbine of an average capacity of 2 ± 0.4 MW and an average rotor diameter of 80 ± 20 meters and a Levelised Cost Of Electricity (LCOE) of 0.053 €/kWh (for year 2017) (IRENA, 2018). LCOE is defined as the cost to produce 1 MWh of electricity with a given technology and is the sum of the annualized investment costs, the fuel costs, the operational and management costs and the carbon costs (Kost et al., 2018).

The on-shore wind farms were selected over the offshore ones because their LCOE is comparable to the other technologies modelled in the model (IRENA, 2018). All producers can sell the produced electricity to the electricity markets. The profit of the producers is a function of subsidy, operating cost, and the market price in a particular moment. The market for selling electricity is chosen based on the difference between the nominated supply and actual supply. If the actual supply is less than or equal to the nominated supply, day ahead market price is used for profit calculation. However, if the actual supply is more than the nominated supply, the extra production is placed on the imbalance market and the imbalance market price is considered for profit calculation, if their provided reserves are engaged on imbalance market. At the start of the model run, all renewable energy producers are randomly assigned a production strategy, which divides them into two strategic groups:

a) Non-storing producers: RE producers who do not own storage but in cases of grid imbalance can curtail their production.

b) Storing producers: Storing renewable energy producers who can store electricity when the actual supply exceeds nominated supply. They provide the stored electricity and the available storage capacity as reserves on the imbalance market.

2. Large industries (2 groups)

The large consumers are grouped under the category of industries. All the industries are modelled to produce one unit of product per kWh of electricity consumed. The price of one unit of product is assumed to be 1€. Each industry has a smart metering system; hence, information of their own nominated and the actual consumption is available to all industries in real time. Each of the industries has a maximum capacity of 50% flexibility in their electricity consumption. However, they are divided into four groups, three provide reserves on the imbalance market, while the fourth group does not. The bidding prices for each group are hypothesized and are based on the relative LCOE of other technologies that are included in the study, so that the bidding price of the most expensive reserve is not above the most expensive technology (modelled as an electrolyser) and the price of the cheapest reserves is lower than the LCOE of wind (without subsidy). The groups are labelled as following based on their strategies:

a) Group 0—non-flex: Industries that do not engage in the imbalance market.

b) Group 1—flex: industries that provide reserves at a symmetric price, each industry is randomly assigned a reserves price which is always positive and less than the price of the electricity from the electrolyser

3. Small or medium sized consumers (SMCs) (2 groups)

The households make up this agent group. They are defined by an average electricity consumption of 12 ± 1 kWh/day, which is the average consumption of a European household (Mulder et al., 2013). The consumption pattern of SMCs depends on the time of the day. Each agent in this group is charged with a bill at the end of the year for the amount of electricity that they consume. Half of the consumers also have Photovoltaic (PV) panels and are hence termed prosumers. The electricity produced by prosumers is first used to meet own demand and the extra is placed on the grid. However, if there is no demand for this electricity, the grid operator can decide to cut the injection of electricity from prosumers. The prosumers do not receive the profit for injecting electricity in the grid because it is assumed that the cost of smart meters and the grid operational costs will balance the profit that the prosumers may gain. In the model, this electricity is placed on the day ahead market with a price of 0.08 €/kWh, which is the LCOE of a PV (IRENA, 2014). The prosumers pay a fee for getting access to the grid. In Flanders (Belgium), it is an annual flat fee of 85 €, which is also used in this model to calculate the bill of the prosumers (Masson & Neubourg, 2019). In the model, the SMCs fall into following two categories based on their strategies:

a) Prosumers: SMCs with PV panels

b) Consumers: SMCs without PV panels

All SMCs receive the bill at the end of the year, which is calculated by considering the annual average price of both electricity markets. In case of the prosumer, the self-consumption is billed as 0.

4. Electricity markets

There are two market environments modelled; day ahead market and imbalance market. In the model, all technologies that participate in the market are ranked according to their LCOEs.

An inflexible base load (abbreviated as fixed-prod) is assumed to provide 20% of the average system consumption at an LCOE of 0.02 €/kWh, comparable to the cost of a hydro power plant in Europe (Sacha Alberici, Sil Boeve, Pieter van Breevoort, Yvonne Deng, Sonja Förster et al., 2014, p. 24). 10% of the average system consumption is provided by the flexible or interruptible gas fired power plant (NG plant) at a cost of 0.04 €/kWh (Kost et al., 2018). The renewable energy capacity from the renewable energy producers (RES-wind) is modelled to match at least 0.1% and at maximum a 100% of the average demand of the system. The half of the SMCs is also modelled to own PV panels, the capacity of which as determined to meet the SMC's own average demand per annum. The electricity that is put on the grid by the SMCs is termed as RES-solar.

On the day ahead market, the consumers and producers nominate consumption and production capacity, respectively, for the next 24 hours. The match between the supply and demand defines 24 values of the market price on the next day. This is done based on the merit order of cheaper to expensive technologies that are engaged to provide the supply. In case of limited supply and a day ahead market price higher than 0.1 €/kWh, it is assumed that a backup technology (R-tech) is used to provide the necessary electricity and ensures that the market price does not rise further, and the system remains stable. The price of buying electricity from the backup technology is a constant 0.1 €/kWh. Since consumption defines how much supply will be engaged and never the other way around, the price of day ahead market never drops below the price of the cheapest technology. It also ensures that the day ahead market price never rises above 0.1 €/kWh. The merit order of these technologies from the cheapest to the most expensive is shown in Figure 1-4.

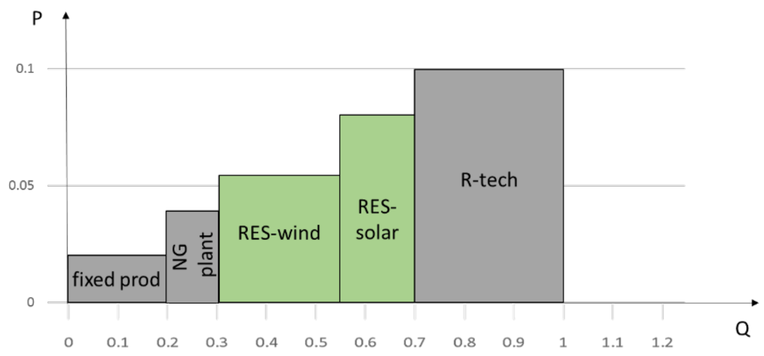


Figure 5-2: Merit order of the technologies that participate in Day Ahead Market (P = price of electricity, Q = installed capacity shown as ratio to the average system demand).

Increasing levels of RES-wind capacity and RES-solar are expected to stabilize the day ahead market price at a lower value. However, in the case of low demand, a higher production capacity may lead to a surge in the injection and would require to be settled in the imbalance market. The imbalance market is a quarter hourly market and hence operates to balance mismatch between supply and demand at a time scale of fifteen minutes. The default value for imbalance market price is 0 €/kWh, unless the demand or supply deviate from their day ahead nominations, causing an imbalance. The former triggers a downward activation, which means that the reserves are requested to decrease consumption or an upward activation from the renewable energy producers is required. The agents who engage in the imbalance market are the industries who provide reserves and the wind energy producers. The other technologies in imbalance market consist of a flexible Natural Gas (NG) fired power plant with a bid price of 0.04 €/kWh, and an electrolyser with a symmetric bid price of 0.2 €/kWh. The merit order of these reserves is provided in Figure 5-3.

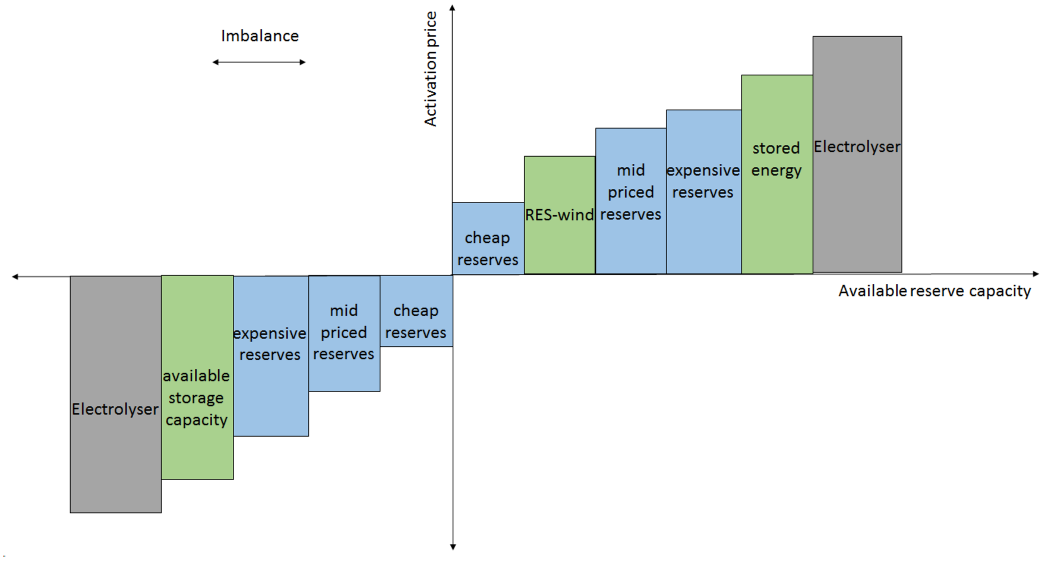


Figure 5-3: Bid ladder for reserves activation, without a feed-in tariff for wind farms.

The model includes a number of parameters for the agents, technologies, and the market environments that have been explained above. In addition, during the simulation runs, the flow of electricity and money between the agents is governed by different variables that again define the state of the agents, technologies, and the market environments. Table 5-1 provides the information for the technologies and the market environment.

Table 5-1: Parameters and state variables.

	Definition	Values	Unit
	Parameters (Do Not Change during the Simulation Runs)		
C_{pv}	LCOE[1] of photovoltaic panels calculated over 20 years period (IRENA, 2014).	0.088	€/kWh
C_{wind}	LCOE of wind turbines calculated over a time period of 20 years (IRENA, 2014)	0.053	€/kWh
τ	feed-in tariffs given to the producers based on data from Belgium	0–0.04	€/kWh
Δ_x	total production capacity of wind farms as a ratio of average system consumption. $_x$ represents the ratio	0–100	%
v-wind	average wind velocity in Belgium (Government of Flanders, n.d.)	4	m/s
C_{tech}	price of electricity bought and sold to the backup technology that can balance the grid imbalances and is engaged a day ahead of actual supply. The hypothetical value of 0.1 €/kWh is considered because this is higher than the LCOE of photovoltaic panels but still comparable to LCOE of biogas power plants (Kost et al., 2018)	0.1	€/kWh

β_{electro}	symmetric bidding price of electrolyser. Depending on the country the price may vary (team, 2019)	0.2	€/kWh
β_{wind}	bidding price of energy from wind farms	0.06	€/kWh
β_{store}	bidding price for the electricity provided or consumed by battery storage of wind farm owners	0.18	€/kWh
Δ_{inflex}	capacity of inflexible power production system	20% of average demand	kW
Δ_{tech}	capacity of the back-up system	∞	kW
C_{inflex}	LCOE of inflexible hydro power production system	0.02	€/kWh
Δ_{NG}	sum of capacity provided by the flexible natural gas plant that participates in day ahead market[3]	10% of average demand	kW
C_{NG}	LCOE of the flexible natural gas fired power plant (Kost et al., 2018)	0.04	€/kWh
	State variables (may change in every time step)		
w_{pred}	predicted wind intensity at that quarter on the next day	0–1	range
s_{pred}	predicted solar irradiation at that quarter on the next day	0–1	range
$DAM.S_{pred}$	predicted and engaged supply to meet the demand on day ahead market		kWh
$DAM.D_{pred}$	predicted demand from the system on day ahead market		kWh
$RES.w_{pred}$	total predicted production from the wind farms		kWh
$RES.s_{pred}$	total predicted production from prosumers		kWh
$RES.w_{act}$	total production from the wind farms in real time		kWh
$DAM.S_{act}$	supply in real time before balancing		kWh
$DAM.D_{act}$	demand in real time before balancing		kWh
C_{DAM}	day ahead market price of electricity	−0.15–0.15	€/kWh
w_{act}	wind intensity in real-time	0–1	range
s_{act}	solar irradiation in real-time	0–1	range
$RES.s_{act}$	total production from the prosumers in real time		kWh
$RES.w_{IM}$	production from wind farms that has been made available to balance the grid at β_{wind}		kWh

$RES.w_{store}$	production from storing agents that has been made available to balance the grid at β_{store}		
R_{wind}	ratio of the RES-wind-act that is needed for activation on imbalance market		%
R_{tech}	capacity activated from the backup technology for balancing day ahead market		kWh
R_{bid}	ratio of capacity activated from the industrial reserves to meet balance the grid		0-1
Δ_{bids}	sum of flexible capacity provided by industries $\sum \alpha_{bid} . R_{bid}$		kW
$C_{DAM.annum}$	annual day ahead market price. $\sum_{i=0}^{34656} C_{DAM} /34656$		
$C_{IM.annum}$	annual imbalance market[4] price. $\sum_{i=0}^{34656} C_{IM} /34656$		
C_{IM}	imbalance market price	−0.2–0.2	€/kWh
$Q_{RE\%}$	percentage of the total yearly demand of the system met by renewable energy producers	0–100	%
Small and medium sized consumers			
	Agent properties (do not change during the simulation runs)		
α_{SMC}	consumption capacity of a household (Mulder et al., 2013)	0.125	kWh
Δ_{PV}	capacity of photovoltaic panels of one household (Mulder et al., 2013)	1–2	kWh
	Agent Variables (may change in every time step)		
α_{pred}	predicted consumption for one quarter of an hour on the next day		
α_{act}	actual consumption in real time		
random. factor	a number generated every quarter of an hour to introduce randomness in the consumption profile of the consumers	0.01–0.05	
Q_{PV}	production from the photovoltaic panels in real time		
$\alpha_{self-cons}$	consumption from own PV panel (only for prosumers)		
Q_{SMC}	production from the PV-panels in real time that is planned for the $DAM.S_{pred}$		
$bill$	bill for the whole past year		€
$bill_{unit}$	per unit cost of electricity consumed in the past year		€/kWh

Industry			
Agent properties (do not change during the simulation runs)			
α_{ind}	average consumption of an industry	2000 (±400)	kWh
group	group number defining the strategy of the industry Group 0: bid-cap of 0 kW Group 1, bid-cap of 0 to 100% of α_{ind}	0 or 1	
Agent variables (may change in every time step)			
α_{pred}	predicted consumption for one quarter of an hour on the next day		
α_{act}	actual consumption in real time		
α_{bid}	for group 0, $\alpha_{bid} = 0$ for group 1, $\alpha_{bid} = 0 - 1$		kW
α_{IM}	for group 0, $\alpha_{IM} = \alpha_{act} - \alpha_{pred}$ for group 1, $\alpha_{IM} = R_{bid}.\alpha_{bid}$		
α_{tot}	total consumption in the past month		kWh
β_{bid}	Bidding price	$0 - 0.2$	€/kWh
$bill$	bill for the past month		€
P	instantaneous profit in every time step		€
P_{unit}	unitary profit for the past month		€/kWh
Renewable energy producers			
Agent properties (do not change during the simulation runs)			
Δ_{prod}	average production capacity of a wind farm	4000 (±100)	kW
$\Delta_{storage}$	average storage capacity	20% of Δ_{prod}	kW
C_{cur}	costs for curtailing (Joos & Staffell, 2018)	0.022	€/kWh
C_{st}	LCOE[1] of battery storage (Wilson, n.d.)	0.176	€/kWh
strategy	strategy defining if the producer will have storage or not If 0, there is no storage facility If 1, there is storage facility	0 or 1	
Agent variables (may change in every time step)			
$\Delta_{req(D+1)}$	Required production per agent to meet the system demand		kWh

Q_{nom}	nominated power production for the next day	kWh
Q_{prod}	actual power production in real time	kWh
Q_{act}	part or all of the Q_{prod} made available for the system	kWh
Q_{curt}	curtailed power	kWh
$Q_{stored(t)}$	stored power in real time	kWh
Q_{DAM}	production sold at the day ahead market, $always \leq Q_{nom}$	kWh
Q_{bid}	production bid at the imbalance market	kWh
Q_{IM}	production sold at the imbalance market If, $\mathrm{R_{wind}} > 0$ $Q_{IM} = \mathrm{R_{wind}} * Q_{bid}$	kWh
Q_{tot}	$Q_{DAM} + Q_{IM} + Q_{IM.st}$	kWh
Q_{sum}	total production traded in the markets in the past month	kWh
$Q_{IM.st}$	storage reserve engaged by imbalance market. Value is positive when batteries are discharged, and negative when batteries are charged	kWh
P	instantaneous profit in every time step	€
P_{unit}	unitary profit for the past month	€/kWh

LCOE[1]; Levelised Cost of Electricity

For the data on wind velocity and solar irradiation, the database of Belgian Electricity Transmission System Operator, Elia was used (*About Elia - Elia*, n.d.). The data on wind velocity and solar irradiation are not meant to depict the exact values but create a realistic pattern of wind speed and solar irradiation in a year for Belgium.

5.1.3 Process Overview and Scheduling

After the model has been set up, the model is run in the following order:

1. Predicting consumption and production for the next day,
2. Setting a day ahead market price for each hour of the day,
3. Actual consumption and production in every quarter,
4. Calculating the system imbalance to decide to engage the imbalance market,
5. Based on the imbalance, setting the imbalance market price for every 15 minutes,
6. Updating the system variables,
7. Calculating profits,
8. Storing the unitary profits of producers and industries at the end of every month,
9. At the end of the year, calculate the bill for SMCs.

The sequence of actions for the model is depicted in Figure 5-4.

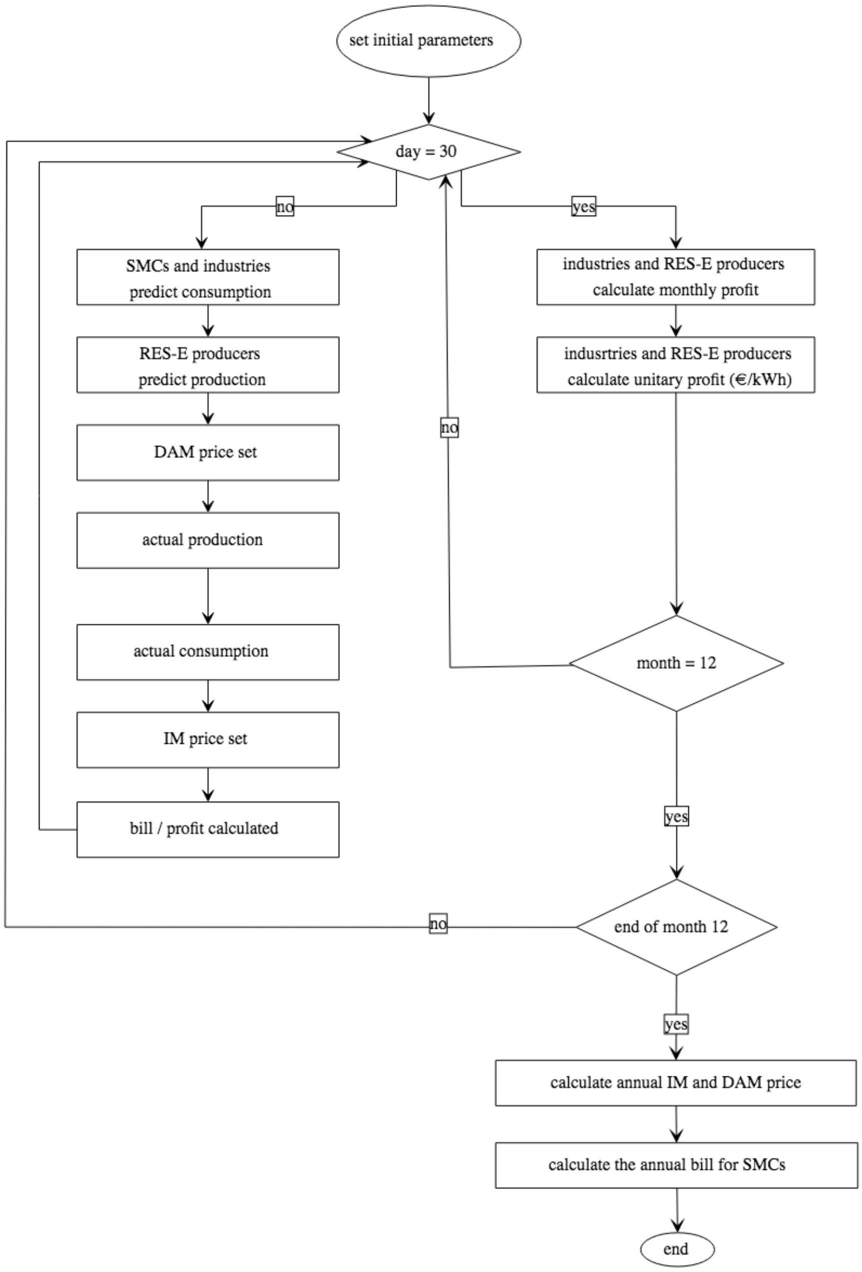


Figure 5-4: Process overview of the model.

5.1.4 Sub-Models

1. Prediction of Consumption and Production

The model process begins on day = 0 and tick = 0, which depicts the hour 00:00 of a day. For the first quarter of an hour (one time step), the industries and SMCs predict consumption for the same quarter on the next day. The prosumers from the SMCs also predict the production from the PV panels, as Q_{PV} depending on the capacity of their solar panels (Δ_{PV}). The producers calculate their production ($\mathrm{Q_{prod}}$) based on the weather predictions for that quarter on the next day. For all renewable energy producers, $\mathrm{Q_{prod}}$ is calculated as a product of their capacity (Δ_{prod}) and the predicted weather (w_{pred}).

Based on the strategy of the producer, the predicted production varies. For non-storing agents, it is equal to their Q_{prod}, while, for storing agents, $\Delta_{req(D+1)}$ and $Q_{pred.stored}$ define Q_{nom}, where $Q_{pred.stored}$ is the expected power production that will be stored, given that $Q_{pred.stored}$ does not exceed $\Delta_{storage}$. Hence, the $\mathrm{Q_{nom}}$ is based on Equation (5-1) or (5-3), and the value for $Q_{pred.stored(t+1)}$ is based on Equation (5-2),(5-4), or (5-5). The conditions that define which equation is chosen for setting the values are explained below:

If $\Delta_{req(D+1)} \geq Q_{prod} + Q_{pred.stored(t)}$, then

$$\mathrm{Q_{nom}} = \mathrm{Q_{prod}} + \mathrm{Q_{pred.stored(t)}}, \tag{5-1}$$

$$Q_{pred.stored(t+1)} = 0. \tag{5-2}$$

If $\Delta_{req(D+1)} < Q_{prod} + Q_{pred.stored(t)}$, then

$$\mathrm{Q_{nom}} = \Delta_{req(D+1)} \,. \tag{5-3}$$

If $\Delta_{storage} \geq Q_{prod} + Q_{pred.stored(t)} - Q_{nom}$

$$Q_{pred.stored(t+1)} = Q_{prod} + Q_{pred.stored(t)} - Q_{nom} \,. \tag{5-4}$$

Otherwise,

$$Q_{pred.stored(t+1)} = \Delta_{storage}. \tag{5-5}$$

2. Setting the Day Ahead Market Price

Day ahead market price is calculated by a merit order economic dispatch procedure. First, the total predicted demand ($DAM.D_{pred}$) is calculated by summing the consumption ($\sum_{i=1}^{n.ind} \alpha_{pred} + \sum_{i=1}^{n.SMC} \alpha_{pred}$) and then matched with the available supply from different technologies arranged in order of increasing bid price.

The technology prices in ascending order are: $\mathrm{C}_{inflex}, \mathrm{C}_{NG}, \beta_{wind}, \mathrm{C}_{pv}, \mathrm{C}_{tech}$.

Once the supply volume is matched to the demand, the total predicted supply can be calculated as:

$$DAM.S_{pred} = \Delta_{inflex} + (R_{NG} \cdot \Delta_{NG}) + (R_{wind} \cdot RES.w_{act}) + \left(R_{solar} \cdot RES.s_{pred}\right) + R_{tech}), \tag{5-6}$$

where

$$R_{tech} = DAM.D_{pred} - \left(\Delta_{inflex} + (R_{NG} \cdot \Delta_{NG}) + \left(R_{wind} \cdot RES.w_{act}\right) + \left(R_{solar} \cdot RES.s_{pred}\right)\right. \tag{5-7}$$

Since this process sets a price for every quarter, it is not representative of the day ahead market price. Hence, at the end of every four ticks (four quarters), the values of the last four day ahead market prices are averaged and one market price for the one whole hour is set. In this way on the next day, there are 24 day ahead market prices for each hour of the day.

3. Actual Consumption and Production

Once day 1 begins, the industries consume electricity according to the time of the day and the day of the week and their strategy. The SMCs consume electricity based on their respective profile and according to the time of the day, week of the month, and season.

For all SMCs, there consumption is a product of their predicted consumption (α_{pred}) and a random factor.

For consumers, α_{act} is the same as α_{cons}

For prosumers

If $\alpha_{cons} \geq Q_{PV}$

$$Q_{SMC} = 0, \tag{5-8}$$

$$\alpha_{self-cons} = |Q_{PV} - \alpha_{cons}|, \tag{5-9}$$

$$\alpha_{act} = \alpha_{cons} - Q_{PV}. \tag{5-10}$$

If $\alpha_{cons} \leq Q_{PV}$

$$\alpha_{self-cons} = \alpha_{cons}, \tag{5-11}$$

$$Q_{SMC} = Q_{PV} - \alpha_{self-cons}, \tag{5-12}$$

$$\alpha_{act} = 0. \tag{5-13}$$

The consumption from all SMCs and industries ($\sum_{i=1}^{n.SMC+n.ind} \alpha_{act}$) sets the value for the day ahead market.

The renewable energy producers produce electricity according to the weather conditions, and their production is calculated based on their respective strategy.

For non-storing producers, they nominate production volumes first on the day ahead market, based on their knowledge of the expected consumption. In the model, this knowledge was substituted by using the total consumption demand of the system as an indicator for the expected demand. Which volumes will be offered on day ahead market and what will be offered to the imbalance market are calculated as follows:

If $Q_{act} - Q_{nom} \geq 0$

$$Q_{DAM} = Q_{nom}, \tag{5-14}$$

$$Q_{bid} = Q_{act} - Q_{DAM}. \tag{5-15}$$

If $Q_{act} - Q_{nom} < 0$

$$Q_{DAM} = Q_{act}, \tag{5-16}$$

$$Q_{bid} = 0 \tag{5-17}$$

for storing producers

If $Q_{act} - Q_{nom} \geq 0$ and $\Delta_{storage} - Q_{stored(t-1)} \geq Q_{act} - Q_{nom}$,

$$Q_{DAM} = Q_{nom}, \tag{5-18}$$

$$Q_{bid} = 0, \tag{5-19}$$

$$Q_{stored(t)} = Q_{act} - Q_{nom} + Q_{stored(t-1)}. \tag{5-20}$$

If $Q_{act} - Q_{nom} \geq 0$ and $\Delta_{storage} - Q_{stored(t-1)} < Q_{act} - Q_{nom}$,

$$Q_{DAM} = Q_{nom}, \tag{5-21}$$

$$Q_{stored(t)} = \Delta_{storage}, \tag{5-22}$$

$$Q_{bid} = Q_{stored(t)} + Q_{act} - Q_{DAM}. \tag{5-23}$$

If $Q_{act} - Q_{nom} < 0$ and $Q_{stored(t-1)} \leq Q_{act} - Q_{nom}$,

$$Q_{DAM} = Q_{nom}, \tag{5-24}$$

$$Q_{bid} = 0, \tag{5-25}$$

$$Q_{stored(t)} = Q_{stored(t-1)} - (Q_{DAM} - Q_{act}). \tag{5-26}$$

If $Q_{act} - Q_{nom} < 0$ and $Q_{stored(t-1)} > Q_{act} - Q_{nom}$

$$Q_{\text{day ahead market}} = Q_{act} + Q_{stored(t-1)}, \tag{5-27}$$

$$Q_{stored(t)} = 0, \tag{5-28}$$

$$Q_{bid} = 0. \tag{5-29}$$

The Q_{bid} from all renewable energy producers ($\sum_{i=1}^{n.prod} Q_{bid}$) provide the wind energy available for balancing the grid ($RES.w_{imbalance\ market}$).

It has to be mentioned that the storing producers provide $Q_{stored(t)}$ to the grid balancing, the sum of which defines the whole stored electricity reserve ($RES.w_{store}$).

Whether that reserve, or part of it, is engaged, ($Q_{imbalance\ market-st}$) will be declared in the following sub-model. Likewise, if the reserves are not engaged and the renewable energy producers do not have the capacity to store the extra production or they do not own storage, then the extra production will be curtailed, setting the value for Q_{curt}.

The sum of production from all renewable energy producers ($\sum_{i=1}^{n.prod} Q_{act}$) defines the value for $RES.w_{act}$

The sum of production from all prosumers ($\sum_{i=1}^{n.SMC} Q_{SMC}$) provides the value for $RES.s_{act}$.

At the end of this step, the supply from the technologies engaged on the previous day is calculated:

$$\text{day ahead market.} S_{act} = \Delta_{inflex} + (R_{NG} \cdot \Delta_{NG}) + RES.w_{act} + RES.s_{act}. \tag{5-30}$$

4. Setting the Imbalance Market Price

Due to weather variations, there is a slight difference between the prediction and actual production, in addition, since the SMCs do not own smart meters, their actual consumption does not coincide with their predicted consumption at all times. Additionally, the inflexible industries (group 0) also do not always respect the nominated demand. This leads to imbalances in the volumes of electricity being fed into the grid and the electricity that is taken-off, setting a non-zero value for IM_{imb}

When $IM_{imb} \neq 0$, the extra demand ($IM.D_{act}$) is adjusted to meet the supply and supply ($IM.S_{act}$) is adjusted to meet the demand, which results in providing values for the following equations:

$$IM.D_{act} = DAM.D_{act} + \Delta_{bids} + \Delta_{store} \cdot R_{store} + Q_{elec}, \tag{5-31}$$

$$IM.S_{act} = DAM.S_{act} + RES.w_{act} \cdot R_{wind} + RES.w_{store} \cdot R_{store} + Q_{elec} \ . \tag{5-32}$$

If the value of IM_{imb} is positive, then the reserves on the right side of Figure A1 are activated, while, if the value is negative, then the reserves on the left side of the figure are activated. The price is set by the most expensive reserve that is engaged to balance the grid.

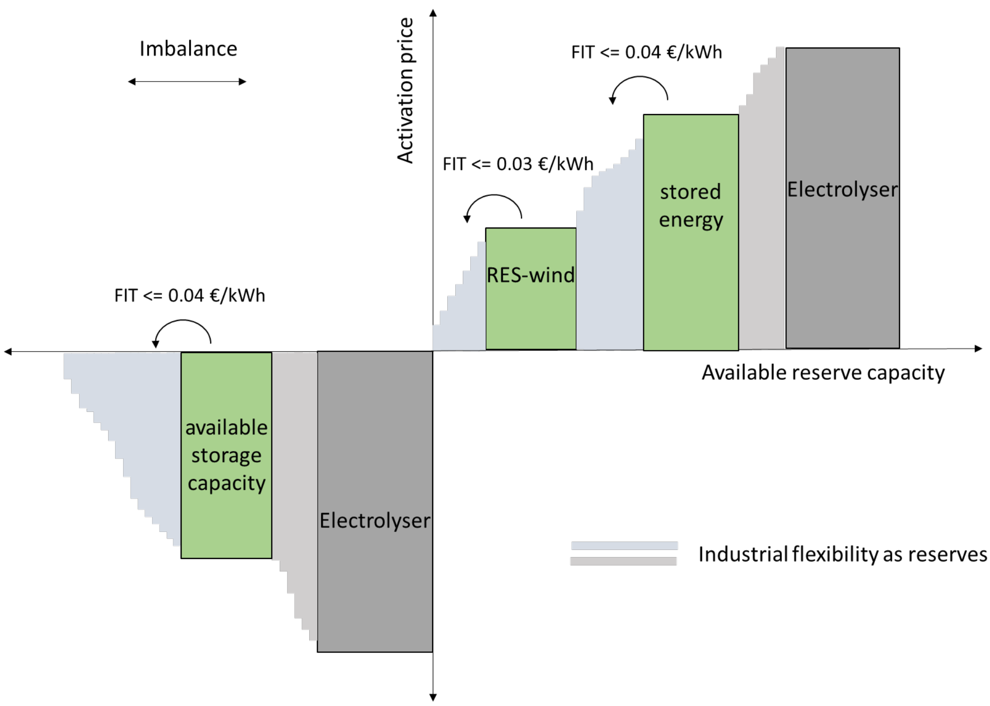


Figure 5-5: Bidding ladder for Imbalance Market.

However, in the presence of τ, energy from wind and electricity from battery storage becomes cheaper and hence moves a step lower in the price ladder. At the end of this step, the reserves that were engaged are declared and each corresponding agent calculates its profit based on these values.

5. Calculating Profit for Industries and renewable energy Producers

Producers' profit is calculated based on which market is used to trade electricity, the bidding price, subsidy level, and curtailed amount of electricity. If the metered volume is less than or equal to the nominated power, then day ahead market price is used for profit calculation. In the other case, the extra production is priced according to imbalance market price only if it is engaged to balance the grid. If the surplus could not be balanced, then the profit is decreased as the cost for curtailing is considered in the equation. For producers with storage, the same procedure is followed for profit calculation, except for stored electrical energy that is used to balance the grid, also increases the costs because of the high LCOE of stored electricity.

For all renewable energy producers:

If Q_{bid} is 0, then values of $Q_{imbalance\ market}$ and Q_{curt} are set to be 0 as well.

If R_{wind} and Q_{bid} are more than 0, then $Q_{imbalance\ market}$ is set as the product of Q_{bid} and R_{wind}. In addition, the value for Q_{curt} is then set at 0.

If R_{wind} is 0 but Q_{bid} is more than 0, then the value of $Q_{imbalance\ market}$ is set to 0 and the Q_{bid} is set as the value for Q_{curt}.

For storing agents:

If $R_{store} \neq 0$, the value for $Q_{imbalance\ market-st}$ is the product of $Q_{stored(t)}$ and R_{store}. What is left from stored electricity after assigning the $Q_{imbalance\ market-st}$ is the new value of stored electricity ($Q_{stored(t+1)}$).

The profit for the storing agents is calculated as

$$P_{prod} = Q_{day\ ahead\ market} \cdot C_{day\ ahead\ market} + Q_{imbalance\ market} \cdot (\beta_{wind} - \tau)) + |Q_{imbalance\ market-st} \cdot \beta store| - [Q_{tot} \cdot \{(C_{wind} - \tau) + (C_{cur} \cdot Q_{curt})\}]. \tag{5-33}$$

The profit for the non-storing agents is calculated as

$$P_{prod} = Q_{day\ ahead\ market} \cdot C_{day\ ahead\ market} + Q_{imbalance\ market} \cdot (\beta_{wind} - \tau) - [Q_{tot} \cdot \{(C_{wind} - \tau) + (C_{cur} \cdot Q_{curt})\}]. \tag{5-34}$$

The total profit gets updated in every time step until, at the end of the year (P_{tot}), it is divided by the total production in the year and the profit/kWh of electricity produced is obtained, P_{unit}. At the end of the simulations the twelve unitary profits (one for each month) are summed and averaged to get an annualised unitary profit for the producers.

The profit for the industries is the remainder of the profit from production of the industrial product and the electricity bill. The profit from the industrial product and electricity consumption is modelled at 1:1. The bill is calculated based on the consumption of electricity and which market the electricity is traded on.

For industries that do not engage in imbalance market, if the consumption is lower than the nominated consumption, then day ahead market price is assigned as electricity cost; otherwise, the imbalance market price is considered as cost. For industries, which engage in imbalance market, the actual consumption is modelled to always match the nominated one. If the reserves are engaged on imbalance market, then, depending on upward activation or downward activation, the consumption is recalculated. The profit is then calculated as follows:

For Group 0,

if actual consumption (α_{act}) is more than predicted consumption (α_{pred}), then the extra consumption is assigned as the consumption from imbalance market ($\alpha_{imbalance\ market}$). Otherwise, the consumption from imbalance market is set at 0.

The profit for Group 0 is calculated as

$$P = (\alpha_{day\ ahead\ market} + \alpha_{imbalance\ market}) - \{(\alpha_{day\ ahead\ market} \cdot C_{day\ ahead\ market}) + (\alpha_{imbalance\ market} \cdot C_{imbalance\ market})\}. \tag{5-35}$$

For Group 1,

the consumption from imbalance market is the product of their respective bidding capacity (Δ_{bid}) and the multiplicative factor (R_{bid}). This multiplicative factor is calculated based on the ascending bidding price of the industries. Starting from the cheapest reserves, till the required capacity is engaged, the price of the most expensive reserve is used. All the reserves that are cheaper are assigned a value 1 for R_{bid}, engaging their whole capacity. For the most expensive reserve, if the capacity is higher than required than R_{bid} is less than 1.

The profit for industries in Group 1 is calculated as follows:

$$P = (\alpha_{day\ ahead\ market} + \alpha_{imbalance\ market}) + |\alpha_{imbalance\ market} \cdot \beta_{bid}| - \alpha_{day\ ahead\ market} \cdot C_{day\ ahead\ market}. \tag{5-36}$$

The total profit gets updated in every time step until, at the end of the month, it is divided by the total consumption in the past month and the unitary profit (€/kWh) (P_{unit}) is obtained.

At the end of the simulations the twelve unitary profits (one for each month) are summed and averaged to get an annualised unitary profit for the industries.

6. Updating the System Variables

In every time step, the predicted values of wind (w_{pred}) and solar irradiation (s_{pred}) are updated and set for the next quarter to be used for the prediction of consumption and production on the next day. In addition, the values for wind (w_{act}) and solar irradiation (s_{act}) in real time are set to be used for grid balancing and imbalance market.

The value of day ahead market price ($C_{day\ ahead\ market}$) that was set on the day before is recalled from the memory and used for the quarter in real time. In addition, imbalance market price ($C_{imbalance\ market}$) for the past quarter is declared and stored for all agents to calculate their respective profit or bill. The value of the total system consumption is updated (Q_{system}); in addition, the variable for the total consumption from the renewables (Q_{RE}) is recalculated and stored.

7. Calculating Bill for the SMCs

At the end of the year, in the last time step of the simulation, the bill for the SMCs is calculated based on the annually averaged value of $C_{day\ ahead\ market}$ and $C_{imbalance\ market}$ and the total consumption in the year.

For the prosumers, self-consumption is not billed; however, a flat fee of 85 €/kW is charged for connection to the grid. This value is based on the prosumer fee that is charged in Flanders (Belgium) (Masson & Neubourg, 2019):

$$\text{bill} = \sum_{i=0}^{34656} \alpha_{act} \cdot (C_{day\ ahead\ market.annum} + C_{imbalance\ market.annum})/2 \tag{5-37}$$

where 34,656 is the total number of quarters in a year, and α_{tot} is calculated as $\alpha_{tot} = \sum_{i=0}^{34656} \alpha_{act}$. The unitary bill (€/kWh) is calculated by dividing the total bill by the total consumption (bill/α_{tot}).

5.1.5 Design Concepts

1. Basic principles

The model is built on the hypothesis that subsidies given to producers of renewable energy cause negative market prices and result in adoption of less flexible consumption practices by the consumers and a lack of incentive for the producers to invest in storage and curtailment mechanisms.

The behaviour of industries and producers is modelled to represent bounded rationality based on the availability of information about own profit.

The market prices included in this model only represent the energy content of the electricity that is traded. In reality, the physical electricity component of the consumers' bill is between 25–30% of the total bill, while 60–75% of the bill consists of taxes, grid fees, transmission and distribution service charges, etc.

2. Emergence

A pattern is expected to emerge when the feed-in tariffs are slowly phased out and the industrial increase their flexible capacity as a response to increasing capacity of wind energy production. This is expected to increase the consumption from renewable energy and decrease the market prices of electricity.

3. Adaptation

Adaptation in the agent-based modelling refers to modelling the agents with properties of memory, learning, and an ability to change their strategy. No adaptation was modelled for these simulations.

4. Objectives

The objective of producers and industries is to maximize their own benefit either by increasing the profit gained by selling electricity or by buying cheap electricity.

5. Learning

No individual or collective learning is included in the model.

6. Prediction

The producers use weather predictions to predict the power produced on the next day. Industries schedule their consumption for the next day based on time of the day.

7. Sensing

The producers and prosumers make use of the available weather information and predict their production. In case of τ, the producers calculate their profit by factoring them in. The industries and SMCs calculate their bill based on the market prices. When there is surplus (deficit) production, the agents respond by providing upward reserves on the imbalance market.

8. Interaction

No interaction was included for the set of simulations carried out for this thesis.

9. Stochasticity

The wind profile data were acquired from Elia's website for the year 2016 and 2018. Each data value from both years was then multiplied with a random value generated around 4.0 m/s (the mean wind speed in Belgium) to introduce randomness in each quarter hour to depict the uncertainty of wind speed. Two inputs are used because the producers are assumed to be located in two different locations. The randomness factor is introduced for calculating the predicted production volumes, while real values are used for calculating the actual production; hence, there is always a chance of slight difference between prediction and actual production.

The data for solar radiation are generated based on the time of the day and the season of the year, and a randomness factor is introduced to depict the unpredictability of weather, and, hence, there is always a chance of a slight difference between the predicted production and actual production by the prosumers. The consumption pattern of industries and SMCs is generated by taking into account the time of the day and the day of the week, whether it is a working day or a weekend. The consumption of SMCs also has randomness included in the actual production to include unpredictability of consumption by agents who have no access to information about their predictions and actual consumption.

10. Collectives

Collectives have been defined under the heading of entities, state variables, and scales.

11. Observation

All of the observations are collected for every quarter hour. When it is the observations that change every month or every three months, the values remain the same for every quarter up to the point that the agents change their strategy and the value changes. The observations collected from the model are:

1) Number of industries,
2) Number of producers,
3) Averaged unitary profit of producers,
4) Averaged unitary profit of industries,
5) Averaged unitary bill of consumers,
6) Averaged unitary bill of prosumers,
7) Annual day ahead market price,
8) Annual imbalance market price,
9) Percentage of system consumption from renewables.

12. Initialization

The model is initialized by setting the total number of SMCs ($\mathrm{n.SMC}$) at 4000. This creates two groups of agents that either have PV panels or not. All SMCs have an average consumption of 0.125 (±0.05) kWh. The total number of industries, $\mathrm{n.ind}$ is calculated by dividing n.SMC by 100. The average consumption (α_{ind}) of all industries is set as 2000 (±400) kWh. The industries are randomly distributed into two groups. The bidding prices for each industry is randomly assigned.

Now, the total required demand of the system, ($\Delta_{\mathrm{max.req}}$) can be calculated by summing the average consumption of all the industries and the SMCs.

The level of τ is also selected from a drop-down list with the options 0, 0.01, 0.02, 0.03, and 0.04 from the interface. From a slider on the interface, the ratio of flexible industrial consumption can be selected between the value of 0 and 1. In addition, from the interface, the percentage of total system demand (Δ_x) is selected from a drop down menu with values, almost 0, 25, 50, 75, and 100%. This provides the information to set the total number of renewable energy producers by dividing the product of $\Delta_{max.req}$ and Δ_x by 500. The producers are randomly divided into groups. One group is assigned storage. The respective capacities and costs for each producer group have already been described.

For all producers, 500 MWh is the average production of a wind turbine considered in the model.

Then, the capacity of inflexible power production system is set at 20% of the $\Delta_{max.req}$. Finally, the capacity of the NG-plant is calculated as 10% of $\Delta_{max.req}$.

5.1.6 Input Data

For the data on wind speed, the statistics on wind power production were downloaded from the website of Belgian Electricity Transmission System Operator, Elia (*About Elia - Elia*, n.d.). The data from year 2016 and 2018 were used to calculate the wind speed by using the formula, wind power (kW) = C_p 1/2 ρ A V^3:

V = Wind speed, m/s,

C_p = 0.59 (theoretical maximum),

ρ = Air density, kg/m^3,

A = Rotor swept area, m^2, and calculated as π x D^2/4

The data on wind speed are not meant to depict the exact values but create a realistic pattern of wind speed in a year for Belgium. The resulting value of wind speed (*wind*) is then used in every time step of the model. The value *w* is multiplied with a random variable with mean 4 m/s (average wind speed of Belgium), to introduce variation in the wind speeds, while volume predictions are made for the day ahead market. The actual value of *w* is used for actual volume production. This value of *w* is then used to calculate the production volume of producers with the formula defined above. The formula used in the code is (3.14 × (rotor-dia)^2 × *wind*)/2. The value of rotor-dia has been defined as 80 (±20) m.

The theoretically maximum value of Cp was used for the calculation of wind power production. This value is considered to not have a significant effect in over-estimation of wind power generation. The reason is, first the production volumes from wind farms in Belgium are used to calculate the wind velocity, using the Cp value of 0.59. Then this velocity was used to estimate the wind production during the simulation, again using the same Cp value (0.59). In essence, the deconstruction of wind power volumes takes place using the same formula, as is used for the recalculation of wind power generation, essentially, resulting in very little variations between real and simulated values.

The data for solar radiation were also generated in the similar manner. The power production from PV panels was downloaded from Elia's website for the year 2018, and the solar radiation (H) was calculated for each quarter of the year by using the formula, solar power (kW) = $A \times r \times H \times PR$:

A = area of solar panels on a household (assumed to be 10 m^2 on average),

r = solar panel yield (assumed to be 40%),

Performance Ratio (PR) = 0.75 (default value),

H = average quarter hourly solar radiation (kW/m^2).

The acquired value of solar irradiation (*solar*) is then loaded into the model for every quarter and solar power is calculated by multiplying this value with the capacity of PV panel of the prosumer. The PV capacity of each prosumer is set as 1 (± 0.100) kW.

The consumption pattern of industries was generated to show the higher consumption during the weekdays and between the hours of 6:00 a.m. and 5:00 p.m., while a maximum consumption of 30% of average consumption was modelled for the night hours and weekends. For SMCs, the hours in the morning between 5:00 a.m. and 9:00 a.m. and hours in the late afternoon between 3:00 p.m. and 7:00 p.m. were modelled to have the highest consumption. Less to almost no consumption was modelled for early afternoon, later in the evening, and at night.

5.2 STATISTICAL ANALYSIS

The three main variables in this study that were varied to test their effect on the whole system are feed-in tariffs (τ), the installed capacity of wind power as a ratio of the average demand of the whole system (ω), and the capacity of flexible consumption from industries (Δ_x). The first two variables are treated as factors, while the variable Δ_x is modelled as a continuous variable. Three response variables were observed in the analyses; $Q_{RE\%}$ (percentage of system demand met by electricity from renewable sources), $C_{DAM.annum}$ (the annualized day ahead market price) and $C_{IM.annum}$ (the annualized imbalance market price). The model was used to run 5500 simulations to generate data that were then fitted with linear regression models using the statistical program R (R Core Team, 2013). All statistical tests were two sided and had a significance level of 0.05%.

CHAPTER 6. FLEXIBILITY AND A LOW-CARBON GRID

Introducing flexibility in the power grid as a response to more renewable energy is a challenging task, as it requires institutional shift to a new way of production and consumption of electricity. Changes in consumer behaviour will be crucial to this shift, which adds to the complexity of this inevitable undertaking. The approach of agent-based modelling has the potential to mimic human actions and captures the system level phenomenon that occur as a result of these actions. The agent-based model presented in this chapter is capable of carrying out a comparative study of cost–benefit distribution between different agents in a grid increasingly fed by renewable power.

Currently, a feed-in tariff of 0.04 €/kWh is given to Belgian renewable energy producers for every unit of wind energy injected into the grid (Flemish Agency Innovation and Entrepreneurship, 2019)—while the installed wind capacity accounts for 13.2% of the total installed power capacity (Elia, 2016). Using Belgium's example, varying levels of feed-in tariffs (τ) (0.01, 0.02, 0.03 and 0.04 €/kWh) are assessed in this chapter, for their effect on the consumption of renewable energy, denoted as $Q_{RE\%}$. Although the example of Belgium is quoted here to design the experiments, the aim is to gain a principle mechanistic understanding in a virtual lab approach rather than analyse a specific case study.

The financial incentives for the renewable energy producers are designed in a way to shift the additional cost to all ratepayers connected to the grid—hence, the more customers shift to responding to RE supply, the less the amount that is paid by the commons (Shum, 2017). To mimic this behaviour, industries are modelled to participate in the imbalance market by providing reserves in the form of flexible demand, at varying levels of reserve prices. This behaviour is hypothesised to reduce the market price of electricity is the annualised imbalance market price, denoted as $C_{IM.annum}$, hence providing societal benefits as a result of actions of a few actors.

The decreasing imbalance market price may increase the utility of the consumers, however, lowered prices means reduced profits for the energy producers. To counter this phenomenon, feed-in tariffs help to boost the production of renewable energy by making renewables more cost efficient, which is expected result in increased production capacity of renewable energy.

The agent based model helped to simulate the effect of increasing the installed capacity of wind farms (ω) (almost 0%, 25%, 50%, 75%, 100%) against linearly increasing flexibility of industrial consumption of electricity (Δ_x), in the presence of different levels of feed-in tariffs (τ), to observe how these three factors; τ, ω, or Δ_x, impact the successful injection of wind energy in the grid. The details of the development of the agent-based model are provided in Chapter 2.

The following section gives the statistical analysis of the simulations and provides linear regression models that define the system outcomes based on the effect of Δ_x, τ, and ω on $Q_{RE\%}$ and the $C_{IM.annum}$. A discussion of profits and bills of different actors is provided to present the ability of the agent-based model to help decision making for policies towards a low carbon grid.

6.1 EFFECT ON THE RENEWABLE ENERGY CONSUMPTION

The effect of the three variables on $Q_{RE\%}$ was first tested at a 95% level of significance and it revealed that in the presence of Δ_x and ω, there is no significant effect of τ on $Q_{RE\%}$. Hence, the linear regression model only includes the effect of Δ_x and ω on $Q_{RE\%}$. Figure 6-1 shows the mean $Q_{RE\%}$, which is noted to increase moderately following the increase in Δ_x, as compared to ω. To quantify the effect of Δ_x and ω on $Q_{RE\%}$, the data were fitted with a linear regression model (Equation (6-1).

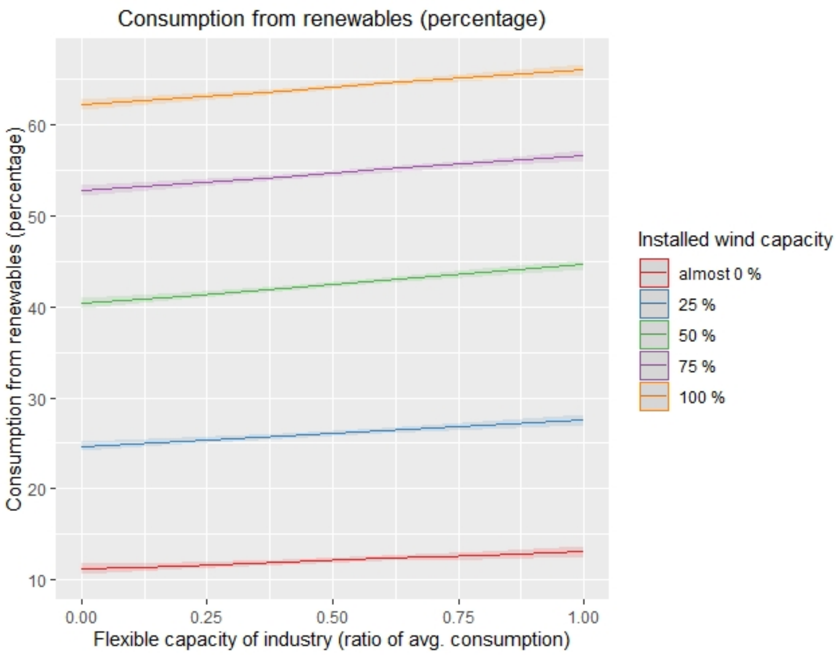


Figure 6-1 Linear regression lines fitted to the observed values of consumption from renewable sources (percentage of total system consumption)

$$\widehat{Q_{RE\%}} = 11.19 + 1.19(\Delta x) + 13.49(\omega_{25}) + 29.15(\omega_{50}) + 41.59(\omega_{75}) + 51.02(\omega_{100}) + 0.96(\Delta x.\omega_{25}) + 2.36(\Delta x.\omega_{50}) + 1.89(\Delta x.\omega_{75}) + 1.93(\Delta x.\omega_{100}) \quad (6\text{-}1)$$

The linear model for $Q_{RE\%}$ explains 94% of the variations in the observed percentage of system consumption from renewable sources with a residual standard error of 4.64%.

It is observed that both factors result in increasing the consumption of renewable energy, with the effect of installed capacity of wind having a more significant effect than the flexibility of electricity consumption. From the trend lines acquired from equation 1, it is shown that ω_{25} results in a 0.28% increase in $Q_{RE\%}$ with every 10% increase in Δ_x ω_{25} results in a 0.28% increase in $Q_{RE\%}$ with every 10% increase in Δ_x; ω_{50} in 4.26%, and ω_{75} and ω_{100} in a 3.8% increase in $Q_{RE\%}$, with every 10% increase in Δ_x. Without considering the effect of Δ_x, there is about a 15% increase in $Q_{RE\%}$ with every 25% increase in the ω.. Whereas, almost flat slopes of increasing $Q_{RE\%}$ are observed under when the effect of increasing Δ_x is considered.

Conclusively, the statistical analysis shows that there is not enough evidence to reject the significant effect of and installed capacity of wind energy and the industrial flexibility on the consumption of renewable energy (p-value $< 2 \times 10^{-16}$).

6.2 EFFECT ON THE MARKET PRICES

The electricity market prices dictate the profits of the industries and the producers and the bill for the households, hence the factors that affect the market prices influence all the agents in a direct or an indirect manner. Day Ahead Market prices showed a significant effect of τ *and* ω, however no significant effect of Δ_x on the day ahead market prices was found (p-value 0.230), also shown in *annex* (Figure A1). It is an obvious result, as the difference in predicted and actual profiles is only apparent in the imbalance market when the flexibility of industries becomes a key in deciding the market prices. Industrial flexibility is not directly related to defining the day ahead market prices. Since, the effect of industrial flexibility is the variable of interest for this chapter, the further statistical analysis of day ahead market prices is not included here. If the reader wishes to learn more about the effect of τ and ω on the day ahead market prices, then I invite them to read the publication[*] that discusses the effect of feed-in tariffs and installed wind capacity on market prices in detail, using the same model.

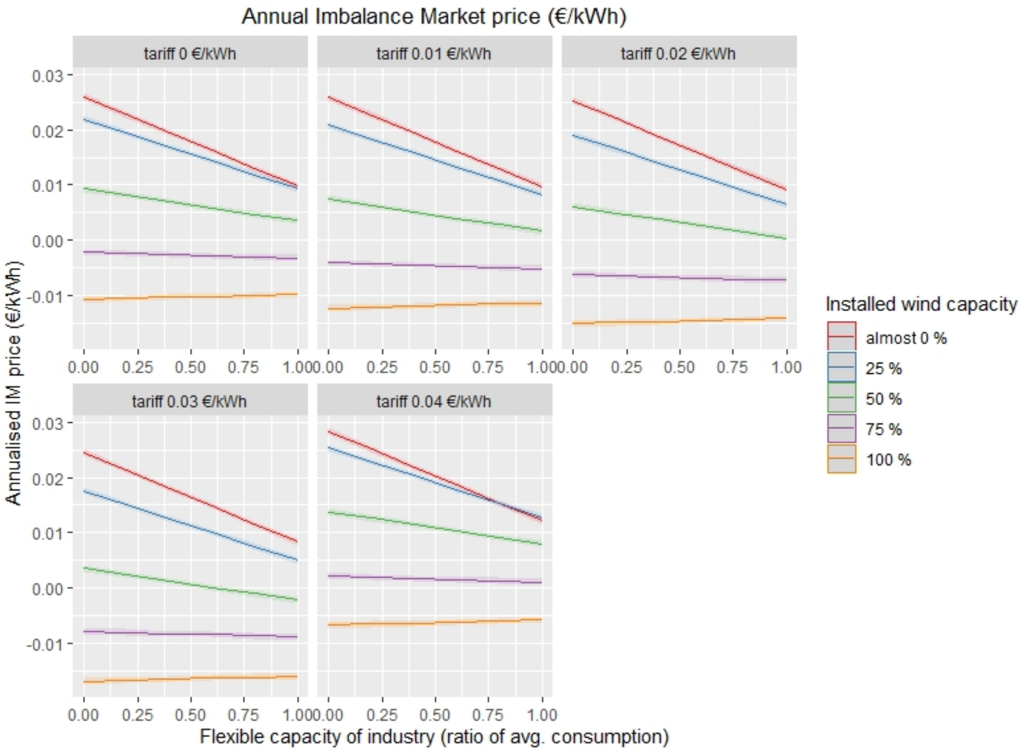


Figure 6-2 Annualised Imbalance Market price observations from the simulations.

The graphs in Figure 6-2 shows the effect of ω and Δ_x on the imbalance market prices under the five different values of τ. The five trend lines for each value of ω are shown in every graph. The linear model from where these trend lines are acquired is given in Equation (6-2) on the next page. This linear regression model has a residual error 0.003% and explains 92% of the variation in the imbalance market prices in a year.

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[*] Maqbool, A. S., Baetens, J., Lotfi, S., Vandevelde, L., & Van Eetvelde, G. (2019). Assessing Financial and Flexibility Incentives for Integrating Wind Energy in the Grid Via Agent-Based Modeling. *Energies*, *12*(22), 4314. https://doi.org/10.3390/en12224314

The imbalance market price above 0 €/kWh suggests that the supply of electricity is less than the demand, and vice versa. It is only for ω_{75} and $\tau_{0.04}$ that the market is closest to being in balance and it is shown by imbalance market price of almost 0 €/kWh. For all values of τ and ω the imbalance market price decreases with increasing Δ_x simply because the industries reduce their consumption and cause the market prices to decrease. It can be observed from Figure 6-2 that the effect of feed-in tariffs follows a similar pattern under the different levels of ω and Δ_x. It is also apparent that once the installed capacity of wind is above the 50% of the demand, the imbalance market price shows a less sharp decrease against the increasing industrial flexibility.

$$
\begin{aligned}
\widehat{C_{IM.annum}} = \; & 0.025 - 0.016(\Delta x) \; - 0.00003(\tau_{0.01}) - 0.006(\tau_{0.02}) - 0.001(\tau_{0.03}) \\
& - 0.002(\tau_{0.04}) - 0.004(\omega_{25}) - 0.016(\omega_{50}) - 0.028(\omega_{75}) \\
& - 0.036(\omega_{100}) + \; 0.036(\Delta x.\omega_{25}) + 0.01(\Delta x.\omega_{50}) \\
& + 0.015(\Delta x.\omega_{75}) + 0.017(\Delta x.\omega_{100}) - \; 0.001(\tau_{0.01}.\omega_{25}) \\
& - 0.002(\tau_{0.02}.\omega_{25}) - 0.002(\tau_{0.03}.\omega_{25}) + 0.001(\tau_{0.04}.\omega_{25}) \\
& - 0.001(\tau_{0.01}.\omega_{50}) - 0.002(\tau_{0.02}.\omega_{50}) - 0.004(\tau_{0.03}.\omega_{50}) \\
& + 0.002(\tau_{0.04}.\omega_{50}) - \; 0.001(\tau_{0.01}.\omega_{75}) - 0.003(\tau_{0.02}.\omega_{75}) \\
& - 0.004(\tau_{0.03}.\omega_{75}) + 0.001(\tau_{0.04}.\omega_{75}) + 0.001(\tau_{0.01}.\omega_{100}) \\
& - 0.003(\tau_{0.02}.\omega_{100}) - 0.004(\tau_{0.03}.\omega_{100}) + 0.001(\tau_{0.04}.\omega_{100})
\end{aligned}
\tag{6-2}
$$

From eq. (6-2), it is apparent that the three factors results in decreasing the imbalance market price. However, when the three factors are observed altogether, their effect is non-significant and hence not included in the regression model. The effect of $\tau_{0.04}$ is contradicting to the other levels of τ, resulting in an increase in the imbalance market prices as Δ_x increases.

Negative market prices for electricity are a rare phenomenon. In reality, the European energy grid allows the grid imbalances to be reduced from the different countries, while, in this model, the grid is modelled as a stand-alone system, hence negative values on imbalance market are observed more frequently than in reality. The decreasing market prices in the simulations as a result of the increasing installed capacity of wind energy have also been observed in Germany. The authors in (Cludius et al., 2014) have shown that, on the German market, each additional GWh of renewable energy fed to the grid has resulted in lowering the spot market price of electricity by $1.4–1.7/MWh. The authors in (De Vos et al., 2013) found that the negative prices on the day ahead and imbalance markets in Belgium, Germany, and France occur due to low consumption demand and high RE generation expectation; one of the reasons is the current support mechanisms for solar and wind power (De Vos, 2015).

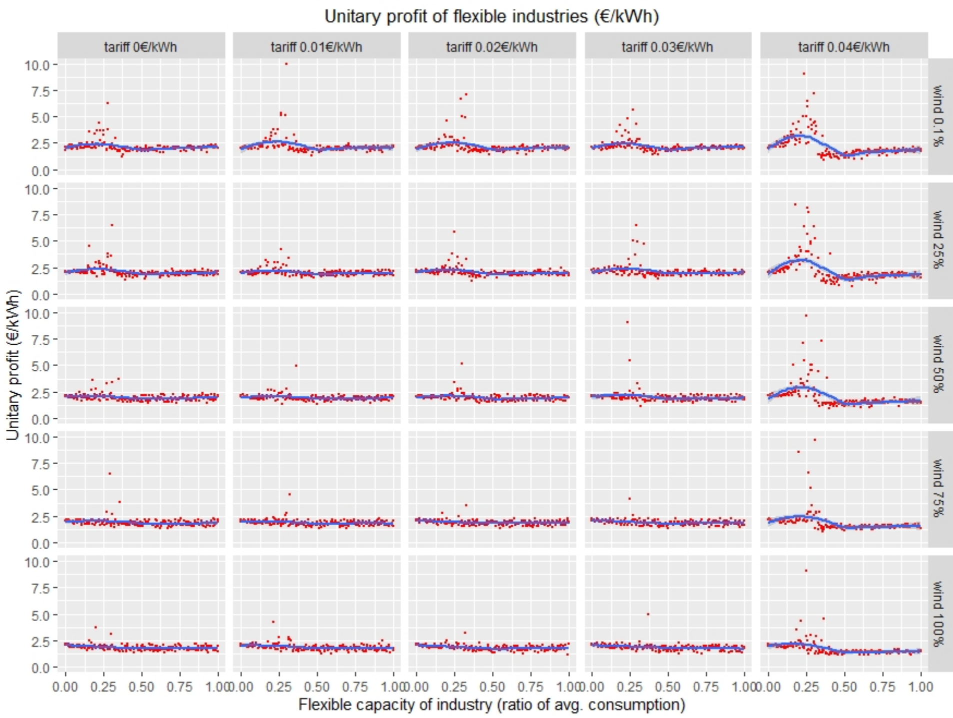
The authors of (Peter D. Lund et al., 2015) mentioned that, if capacity bids from renewable energy are in use on the reserve market, the energy price on reserve markets may get lower than on the intra-day market, creating distorting incentives. The value of imbalance market price is a good KPI for policy makers to decide on the incentives for the different actors in the energy systems. In the following section, the effect of the imbalance market price is explained in reference to the profits and bills of different economic agents.

6.3 EFFECT ON INDUSTRIES

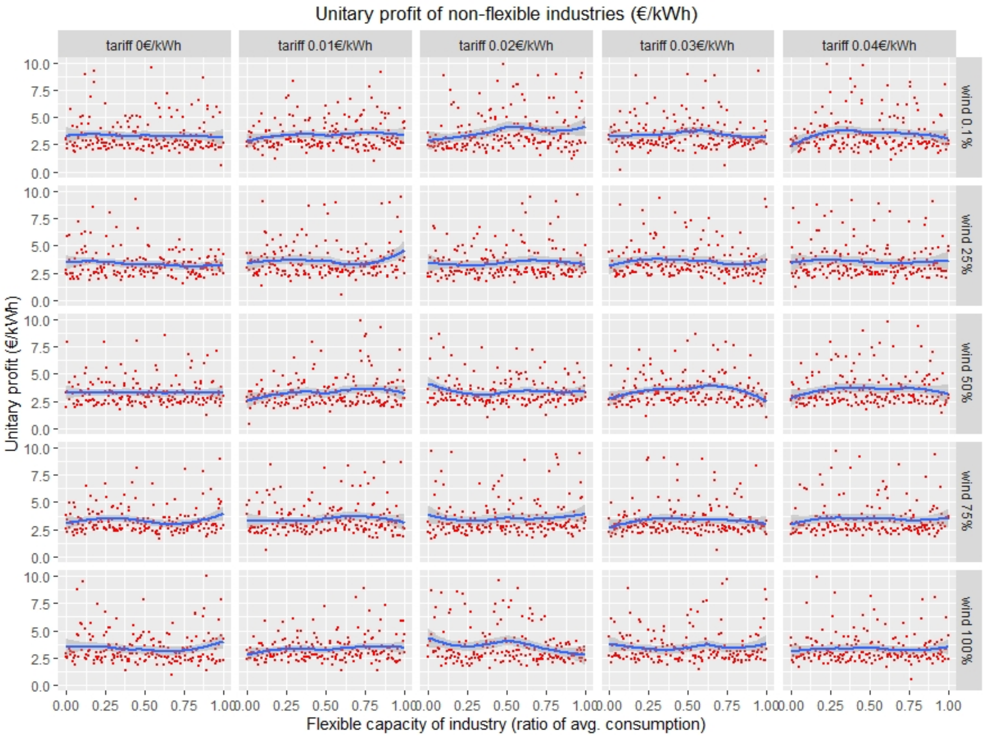
The effect of the three variables on the profits of the industries is shown in Figure 6-3 (a,b). For all simulations, the mean unitary profit of flexible industries is observed to be 2.02 €/kWh, whereas the mean unitary profit for the non-flexible industries is 6.01 €/kWh.

While observing the spread of mean profits of the two industry groups, it is apparent that the industries that are non-flexible have a wider spread as compared to the ones that are flexible. This is a result of modelled randomness in the consumption of the non-flexible industries, who do not respect their consumption profile and hence have a random pattern in their profits. The flexible industries on the other hand are modelled to always respect their consumption profile and only change it once grid imbalances occur.

A deviation in mean profits of flexible industries is observed when the flexibility is less than 50% and a peak is observed at 25% (Figure 6-3a). This effect is most obvious when the value of τ is 0.04 €/kWh. The reason is, at this value of feed-in tariffs the risk of imbalance of the grid is highest, as the wind energy becomes second-cheapest technology on the day ahead market, a high volume of wind energy is expected to be injected in the grid. However, the risk of imbalance increases in real time and this provides industries a chance to gain profits by selling their flexibility. This hike in profits only persists till the flexibility reaches 25%, as a result of simple supply and demand mechanism. Once the available flexibility increases, imbalance market prices begin to decrease and stabilise at 50% flexibility and above.



(a)



(b)

Figure 6-3 (a,b): Mean unitary profit for each industries (€/kWh).

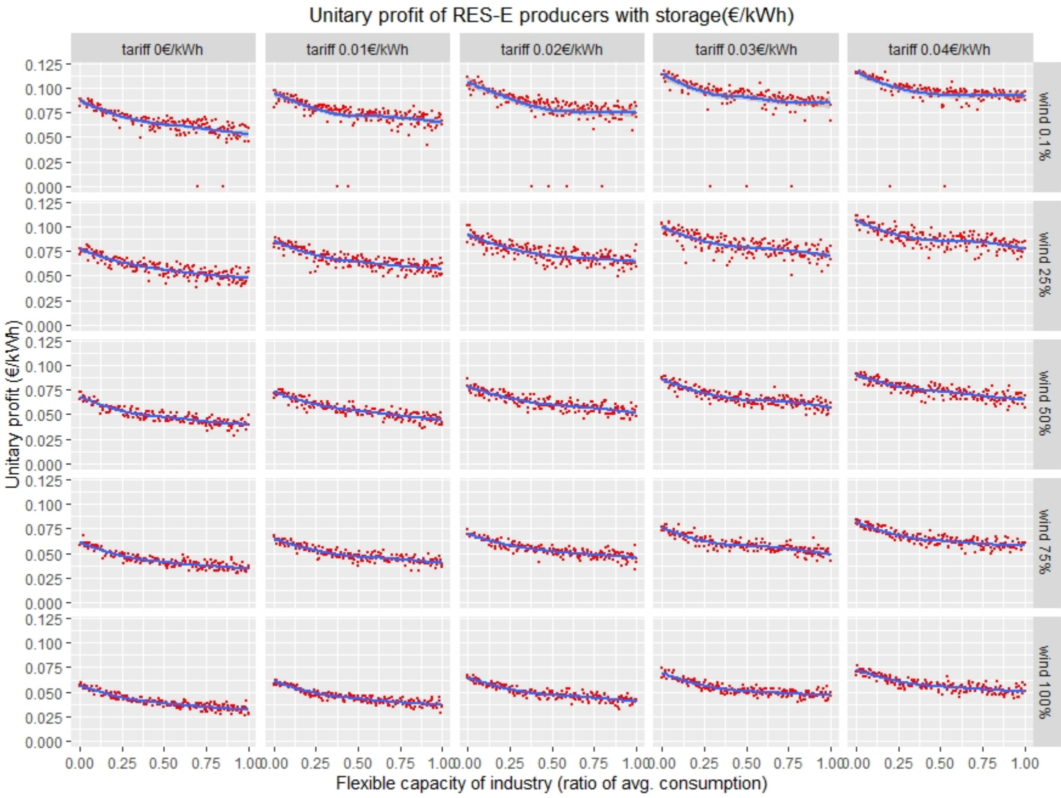
The nearly flat curves of unitary profit of flexible industry in Figure 6-3a show the dilemma that industries face when deciding on being flexible or keep their production uninterrupted. The increasing flexibility of the industries provides an overall system benefit of increasing consumption from renewables, decreasing imbalance market prices but for their own profits this strategy does not prove more beneficial. The dichotomy of system level benefits and individual losses is apparent in this example.

6.4 EFFECT ON THE WIND ENERGY PRODUCERS

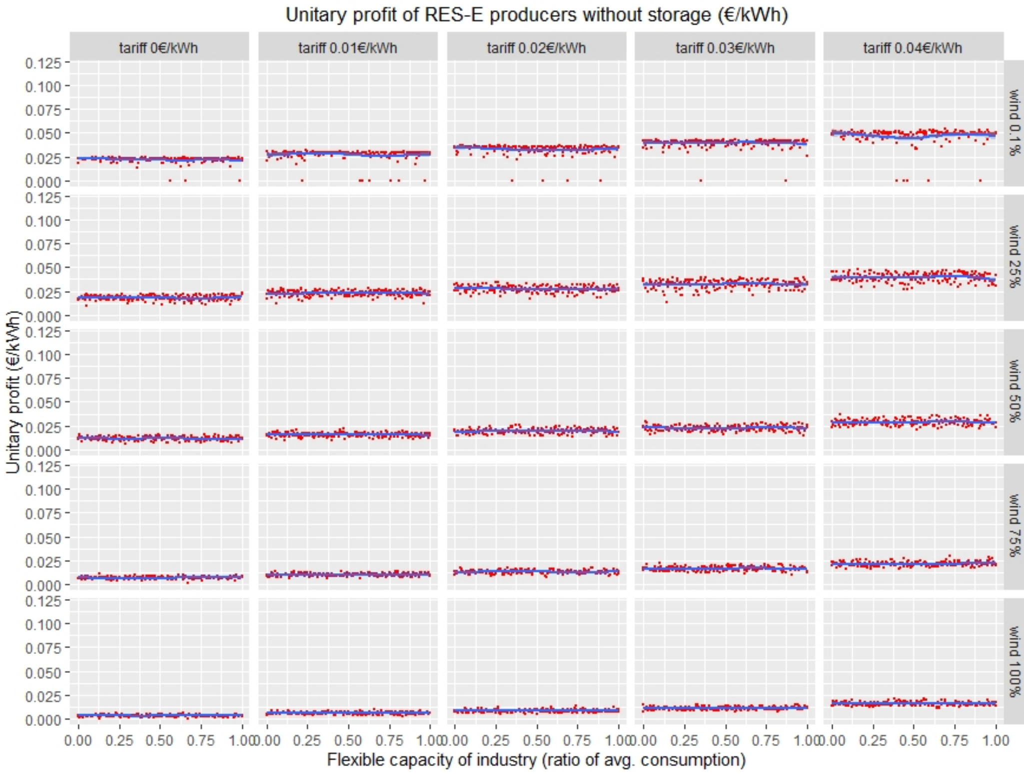
The effects of τ and Δ_x were also assessed for impact on the profits of the two producer groups separately. Figure 6-4a shows the mean unitary profits of storing wind energy producers, where the variation between the different simulations is very narrow and the effect of different feed-in tariffs appears to cause a slight increase in the unitary profits. However, the general trend that can be observed from this figure is of decreasing profits as the flexibility of the industries increases till 30 - 40%, after which the decrease continues but less sharply. On the contrary, Figure 6-4b shows stable mean unitary profits of the non-storing agents, without any effect from the increasing flexibility of industries.

The results support that the renewable energy agents face a push to operate more efficiently when feed-in tariffs phased out and the installed capacity of wind energy increases because their profits decrease. Market mechanisms that dictate fines for deviating from nominated power can further demotivate actors in the power generation business to switch to renewable energy technologies. There need to be other support mechanisms that promote investment in storage facilities for the renewable energy producers. The market mechanisms need to evolve to let more renewable energy producers participate.

The most interesting conclusion from the simulations is that the mean unitary profit of non-storing agents is lower than the storing renewable energy agent; 0.064 €/kWh for storing agents and 0.021 €/kWh for non-storing agents. This result is in contradiction with the results observed in the published work*. The main difference between the characteristics of the producers between this set of results and the published work lies in the adaptation of the strategy. In the publication, the producers adapted their strategy by comparing it with three randomly selected producers for a period of three months. However, for this study, this adaptation is turned off. Hence, it shows that producers with storage gain an overall better profit through the year as compared to the non-storing producers.



(a)



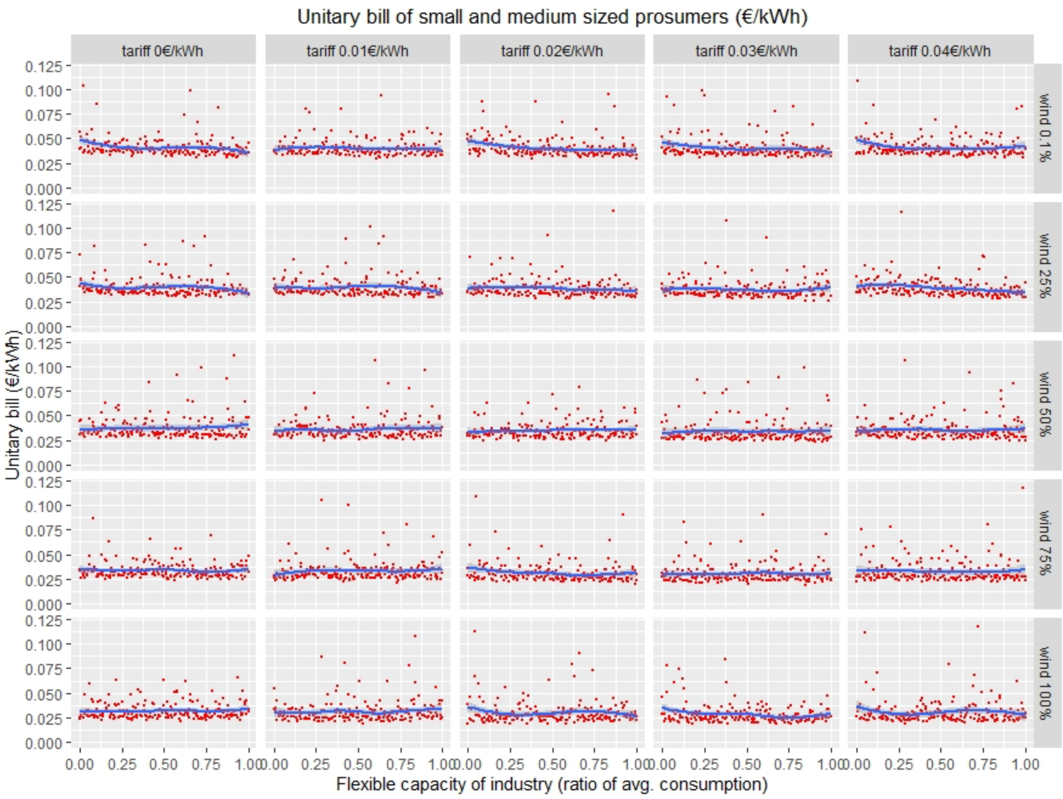
(b)

Figure 6-4 (a,b): Mean unitary profit of producers (€/kWh).

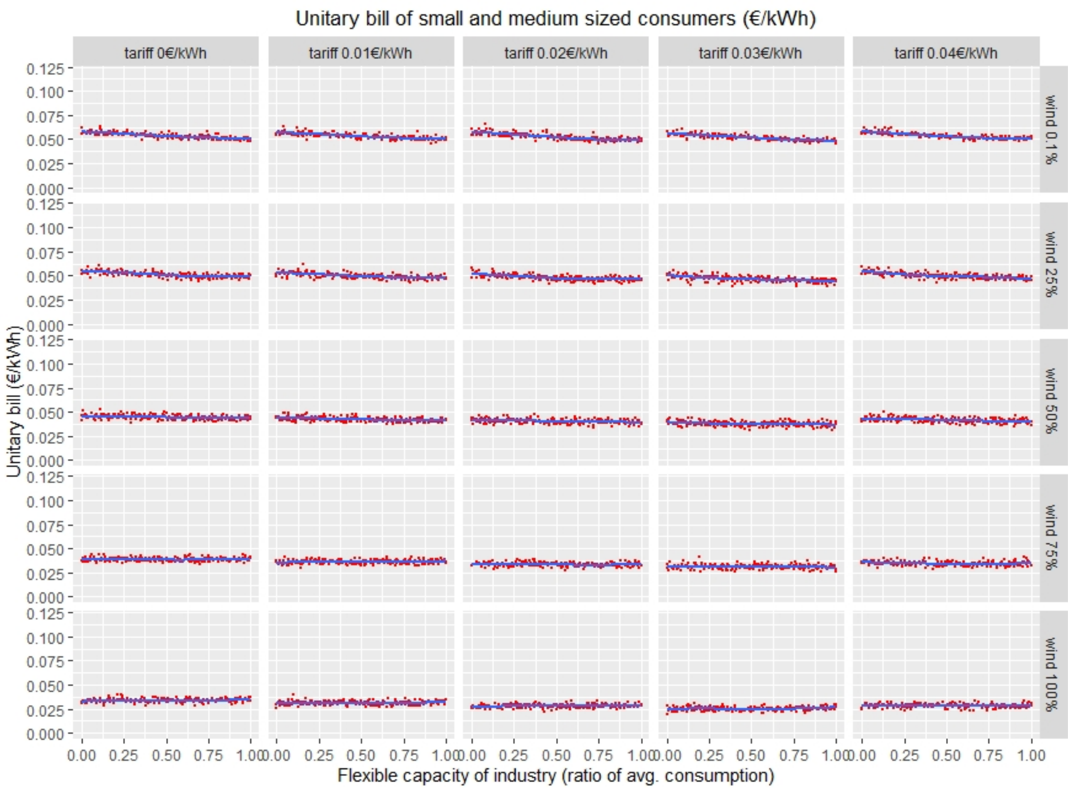
The result of the adaptation behaviour points to the need to simulate the behaviour of the different agents for a longer time period than a year. This will help to observe how the system evolves to self-organise itself and move to a new equilibrium under the changing circumstances.

6.5 EFFECT ON SMALL AND MEDIUM SIZED CONSUMERS

Finally, the mean unitary bill for households with PV panels and without being in relation with increasing values of Δ_x is shown in Figure 6-5 (a, b). When the mean bill of consumers is separated according to the ownership of PV panels, it suggests that it is profitable for households to own PV panels, as compared to the households without PV panels. The unitary bill for the prosumers is 0.034 €/kWh, while it is 0.041 €/kWh for the consumers. There are two factors that cause disparity between the bill of the prosumers and consumers; first, the amount of consumption of electricity from the grid, and, second, the effect of the prosumer tariff. The variation in the bill of the prosumers could be attributed to the variety of sizes of the PV panel sizes and weather patterns that were modelled to mimic reality. The limited variation in the unitary bills of the consumers is very likely a result of unchanged profile of consumption, without an effect from the grid imbalances or weather pattern.



(a) Unitary bill of small and medium sized prosumer



(b) Unitary bill of small and medium sized consumers

Figure 6-5 (a, b): Mean unitary bill (€/kWh) for each Small and Medium Sized Consumer group.

The results of the agent-based model regarding the small and medium sized consumers have a few uncertainties. First, it needs to be mentioned that, since the average of the two market prices is considered for billing the small and medium sized consumers, the bills do not reflect reality. In reality, the supplier would nominate the consumption on the market for the consumers under a contract and the consumers will be billed according to the mismatch from these nominations. Second, the capacity of the PV panels for each household was estimated very conservatively. The average capacity of a PV panels owned by a Belgian household is estimated to be 3 kW (GfK Belgium consortium, 2017), as compared to the 1 kW capacity that was considered in the model. The size of the PV panels for each household and the estimated prosumer tariff is comparable (1kW capacity ≈ 85 €) but it does leave room for improvement of the model in the future. It also needs to be mentioned that in a report by the European Commission on the residential prosumers in Europe, the estimated percentage of households in Belgium with PV panels will increase to 8.7% of the total number of households by 2030 (GfK Belgium consortium, 2017). In the model, it was considered that half of the households own PV panels. Putting these numbers in perspective, it shows that the total capacity of the system to produce solar power may actually be higher in the model, as compared to reality.

The average bill for the small and medium sized consumers observed in the study exhibits an opposite trend to what was observed in Germany, where the electricity price increased by 30% from the year 2006 to 2012, while the average household income grew by 6% (Weber, 2010; Winkler & Altmann, 2012). The discussion on the effect of the move towards a low-carbon grid on the households is an important one, but out of scope for this thesis.

CONCLUDING CASE STUDY-II

Based on the behaviour of the agents, industries and the producers of renewable energy are the two agents that are discussed in a system transition perspective. Although households and small consumers are important actors but their overall impact on the grid and market prices is negligible in this context. This section discusses how the agent-based model can be used to mimic human systems and devise strategies for a low-carbon future.

System behaviour that is dictated by the interaction of wind energy producers and industries is shown in Figure 6-6 and Figure 6-7. The loops with an (R) show a reinforcing loop, which results in more of the same action (growth or decline). Whereas, the loops with a (B) indicate a balancing effect which means the action will find an equilibrium and not increase or decline perpetually.

Extending the results to the strategies of industries and how they will impact the system behaviour, a pattern was observed that was different under the effect of feed-in tariff at 0.04 €/kWh and the rest of the feed-in tariffs. In Figure 6-6, under the effect of τ less than 0.04 €/kWh, the imbalance market prices will decrease with an increasing Δ_x and ω. This will cause the number of wind energy producers with storage to decrease and an increase in the number of flexible industries. As both loops are balancing, the system will find equilibrium and maintain it.

This result shows that once the feed-in tariffs are phased out and the industrial flexibility is placed on the imbalance market, it will result in declining imbalance market prices, which will control the number of producers with storage. Recall that the producers with storage have higher cost, hence they bid their reserves from storage at a higher price than the producers without storage. This will cause grid imbalances to occur, resulting in an opportunity for flexible industries to sell their reserves.

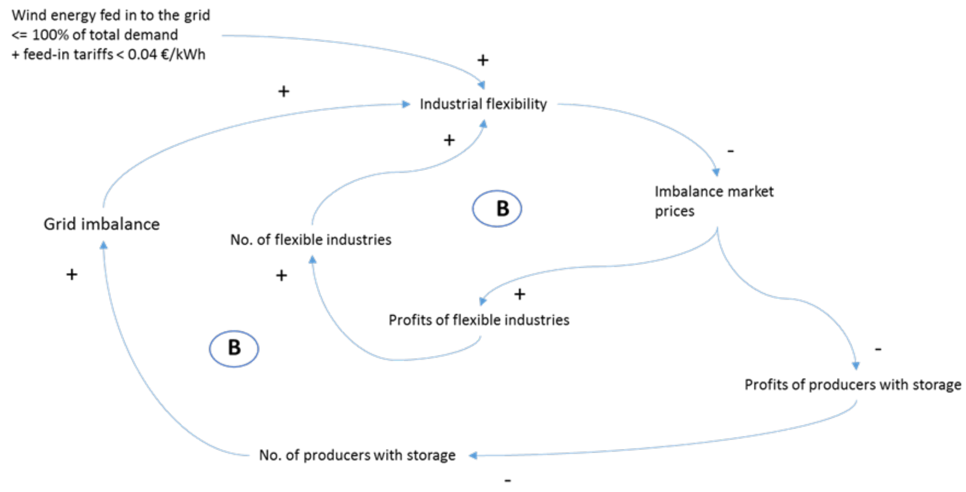
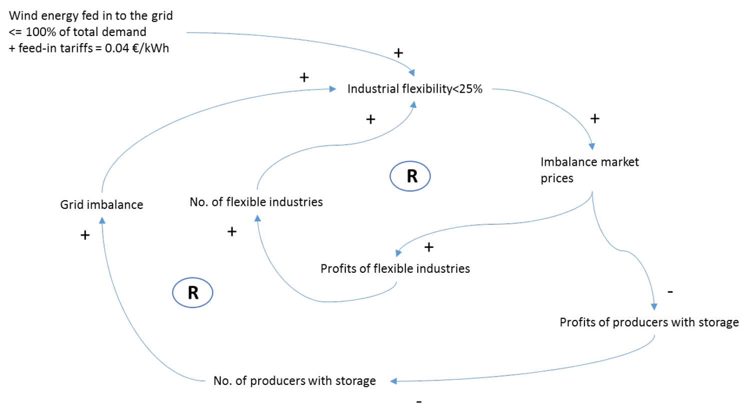


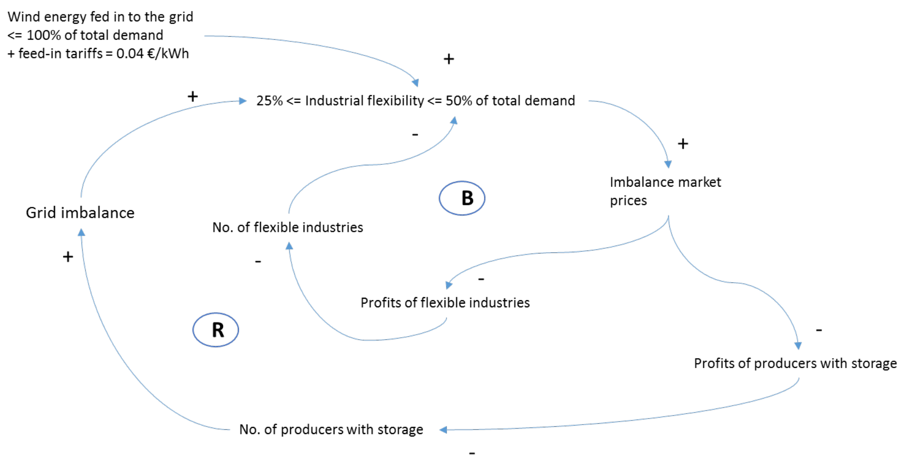
Figure 6-6: Strategies for different agent groups dictated by the imbalance market when ω is <= 100%, maximum Δ_x is than 100%, and τ <0.04 €/kWh

However, when considering the feed-in tariffs at 0.04 €/kWh, the results differ for varying ranges of industrial flexibility, as shown in Figure 6-7. When Δ_x is less than 25% it results in increasing the imbalance market prices, resulting in a reinforcing loop causing a hike in the number of flexible industries (Figure 6-7a). This effect is accompanied by the outer loop that defines the number of wind energy producers with storage, which would keep decreasing and causing more grid imbalances. However, this is only true till Δ_x reaches 25%.

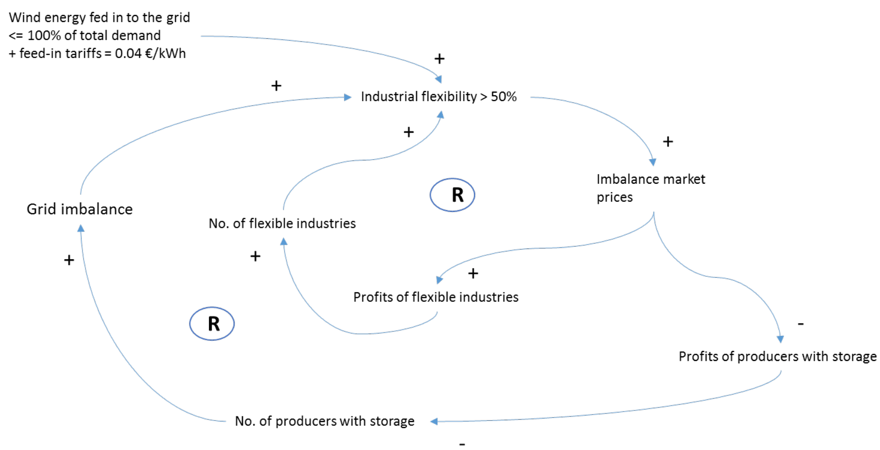
When the flexibility of the industries is increased from 25% to 50%, the imbalance market price increases. However, this increase has a negative effect on the producers with storage. The reason is that the imbalances are met by the industrial reserves and the stored reserves are not activated, resulting in higher costs for the storing producers. This causes the producers without storage to make higher profits (as compared to the storing ones), plunging the grid into imbalances, and very low imbalance market prices. This reinforcing loop is balanced by the flexible industries that will raise their flexibility from 25% to 50%. Although the number of flexible industries will decrease due to their decreasing profits but it will balance the grid, the imbalance market prices and, the number of the non-storing producers. This effect is depicted in the form of a balancing feedback loops in Figure 6-7b. This is not a very profitable situation for the industries and learning from experience, this would result in declining flexibility reserves on the imbalance market.



(a) Maximum industrial flexibility is 25%



(b) Industrial flexibility is between 25 – 50%



(c) Minimum industrial flexibility is more than 50%

Figure 6-7 (a, b, c): Strategies for different agent groups dictated by the imbalance market when ω is <= 100%, value of Δ_x is varying and τ =0.04 €/kWh

When Δ_x is above 50% and τ is 0.04 €/kWh, the profits of flexible industries show a slight increase (Figure 6-3), which may result in increasing the number of flexible industries, as shown in Figure 6-7c. At this point, the increasing profits of industries are a result of very cheap electricity that is available to the system, in addition to the profits that flexible industries make by selling their capacity on the imbalance market. If there is no cap on the wind energy being fed into the grid, this increase in imbalance market prices will keep on going, resulting in more flexible industries, more producers without storage and more grid imbalance. One has to remember that like all systems on the planet, this system also has its boundaries; defined by the feed-in tariff (0.04 €/kWh) and the wind energy being fed into the grid (100%).

In all figures (a,b,c) of Figure 6-7, the number of producers with storage shows a decline, reinforcing grid imbalances. These results indicate the contradiction in the benefits for the flexible producers (with storage) and the flexible industry. However, this can be balanced by public intervention that is not only based on feed-in tariffs. The investment in research and development of cheaper storage technologies and removing the protection from market effect on the renewable energy producers who cause grid imbalances, will aide in the move to a low-carbon future.

Concluding the strategies for top-down incentives for the move to a low-carbon grid, it is observed that once the feed-in tariffs are phased out, the producers with storage will be affected adversely, as the price of storage still remains very high. This effect will be worsened if the industries will be enabled to provide flexibility as reserves. In the presence of demand side response, the producers without storage will perform better economically and hence will not be pushed to invest in storage, stagnating the very high storage costs. If the system is allowed to self-organise then the industries will provide maximum of 25% flexibility as reserves and the producers will not invest in storage. This plausible scenario will still require market mechanisms that support demand response and protect the producers of renewable energy from the fines incurred due to imbalances in their portfolio.

CHAPTER 7. DISCUSSION AND CONCLUSION

7.1 DYNAMICS IN THE INDUSTRIAL CLUSTERS

This section answers the first sub-question in light of the first case study which was focused on understanding the preconditions to engage in industrial symbiosis.

The synthesis of the primary and secondary data showed that each cluster in the case study has a unique history that defines the evolution towards industrial symbiosis. The cluster in Dunkirk showed the most advanced stage of symbiosis (institutionalisation and embeddedness), whereas the Rudniki cluster lagged behind in this regard. The symbiosis networks in Humber and Marseille-Fos also have a rich history and there are third parties present in the region that facilitate symbiosis, qualifying them as clusters where symbiosis is embedded and institutionalised. The Visp district heating and cooling network is a rather small network and a limited conclusion on its development stage qualifies it also as a cluster with an institutionalised symbiosis culture.

Looking at the challenges faced by the individual clusters, the cluster in Rudniki (Poland) was hindered in its move to a symbiosis due to the lack of spatial proximity between the industrial sites. The one symbiosis that was identified showed self-organisation of the industries towards the economically beneficial but a conventional symbiosis involving a substitution of primary raw material of cement with a by-product from steel. During the course of the case study the steel and cement industries in Rudniki entered into a direct contract, circumventing a third party vendor who managed the supply before. This shows an improved trust between the two partners, which has been linked as a pre-requisite for industrial symbiosis in some case studies (Boons & Janssen, 2004; Spekkink, 2017).

The Marseille-Fos cluster (France) has evolved from self-organisation to government planning and finally a facilitated (brokerage) network of industries. Just like the cluster in Poland, the symbiotic opportunities in this cluster were hampered by the distance between the two partners. On their individual locations, both industries were embedded in a network of symbiosis with other businesses but there was only one direct connection between them, which involved shared human resource. During the four years of the case study, information exchange between industries was carried out without the breach of confidentiality. The case study helped to communicate the interest of the two partners in exploration of symbiosis, resulting in agreements been signed between the two partners to further communicate about the symbiotic possibilities.

The Humber cluster (UK) showed the results of strong commitment to industrial symbiosis in the region. Starting from the large infrastructure based symbioses, that were a combination of self-organised and facilitated (collective learning), it moved to a facilitated by brokerage type of symbiosis. Finally, the cluster has evolved to follow a self-organisation pathway. This has resulted in the industrial members to look for symbiotic partners on their own, without relying on a local entity. This cluster proved to have the highest potential of symbiosis, given that the industries are located rather close to each other. The novel symbiosis that was identified in this cluster involved the selling of a waste liquid fuel from the Chemical's site to the Cement plant. Identification and study of the proposed symbiosis had not only led to a piqued interest from both partners in symbiosis, but also to better resource efficiency in the chemical plant.

The two examples of the district heating networks led to a good understanding of the evolution of the industrial symbiosis surrounding public-private partnership. The Visp DH&CN (Switzerland) has emerged as a result of the self-organisation by the public and private actors. Industrial symbiosis particular to the Dunkirk DHN has first emerged as the facilitation - brokerage by the public authorities and then evolved to facilitation – collective learning. The evolution of the Dunkirk cluster is a good example of public authorities and industries taking a lead and driving the move towards sustainability. This point goes back to the SDGs and the Local Agenda 21, which embodies the objective behind support for industrial innovation – the progress of the society as a whole. The Dunkirk cluster (wider than the heating network) provides lessons for future cities that are in harmony with industrial evolution and vice versa.

In all locations, except for Rudniki, the clusters showed a shift from simple (one-to-one) contracts to the development of new entities and more complex legal formulations in the system. On the one hand, this added to the complexity of the network, on the other it meant better management of the synergies. It translated into improving the system's vulnerability to shocks, as the risks were spread over multiple partners. On the point of vulnerability, the case in Visp is opposite of that and hence the reliance of the network on a single entity is its biggest weakness. It has to be mentioned that the Visp network is a rather small network, in terms of size and the number of partners, as compared to the district heating network of Dunkirk, which makes it understandable that its level of complexity is not as high as in the Dunkirk cluster.

7.2 FACILITATING IDENTIFICATION OF SYMBIOSES

This section answers the second sub-question which focused on the method of facilitation to identify symbiotic opportunities between the participating industries.

There are many methods for identification of industrial symbiosis, such as, surveys, facilitated workshops, brokerage events, self-organised match-making, online platforms, government planning, third party facilitation, etc. These methods have their own set of advantages and challenges. For this thesis the method for symbiosis identification was selected as the LESTS survey, which has a strong focus on the non-technical information concerning the potential symbiotic partners.

The LESTS survey and the accompanying interviews fulfilled the conceptual objective of the study; to understand the preconditions for industry to engage in industrial symbiosis and facilitate the identification of opportunities for reduced material and energy waste. The LESTS survey resulted in identifying twenty-eight opportunities for the industries to cooperate. Seventeen opportunities in the Humber cluster, seven for the Lavéra cluster and four industrial symbioses were proposed to the industries in the Rudniki cluster. The LESTS survey helped to understand more than just the technical match-making; it also provided enriching information to develop a whole methodology for identifying symbioses. starting from framing the questionnaires, contacting the key persons, understanding of the contextual information and future demands of the industries and their respective local authorities, finally translating this information into symbiotic opportunities.

Quoting one instance of the importance of non-technical details, the LESTS survey resulted in identification of the suitability of the primary liquid fuel stream to be sent to the cement plant from Chemicals' site. It is worth mentioning that the questions about the existing legal permits were the reason for the identification of the symbiosis activity. This shows a strong point of the LESTS surveys that they help to focus on the obscure symbiotic opportunities and reduce path dependence. Path dependence is identified as a shortcoming when the industrial symbiosis identification focuses entirely on input-output matching (Grant et al., 2010).

Despite the advantages of the LESTS survey, three main conclusions are drawn to improve the LESTS methodology for future use. These conclusions are specific to the situation when the LESTS methodology is being used as part of a public research and innovation project. This distinction is made due to the subjectivity of the observations that were made during the case study. In the case study, the industries had voluntarily participated in the H2020 project and signed agreements to fully cooperate in the research and innovation tasks. This included a PhD student was employed for each sector who provided in depth information for filling in the LESTS survey. For four years the PhD students cooperated on the case study, which is an extraordinary length of time spent on identifying opportunities that did not focus on the core business of the industries. This is a consideration that facilitators of industrial symbiosis have to keep in mind when a lengthy survey as the LESTS is carried out. Hence, the first recommendation is to streamline the LESTS surveys for a better focus on identification of industrial symbiosis. Second, the LESTS methodology lacks in the inclusion of a workshop design that would bring the local partners into contact. Due to the clauses of the H2020 project agreement, the diverse sectors were not contacted for their interest in industrial symbiosis. This was observed to be a significant shortcoming in the case study, which resulted in limiting the number of possible symbiosis. Third, the methodology can bring objective results to prioritise the symbioses if it includes a method to quantify the costs and benefits of the symbioses. For the case study, the symbiosis opportunities were prioritised by the industries based on their interest and SWOTs of individual symbiosis. Finally, the sharable streams were valued based on the material or function that they could potentially substitute. Although this provided enough information to the industries to prioritise the symbioses, it can be improved by including one clear method of quantification of costs and benefits (including People, Planet, Profit).

A recent interest from the public bodies has increased the funding for development of online platforms to facilitate the symbiosis identification. In Europe alone, over €130 million has been invested since 2006 on research projects that enable industrial by developing a methodology, tool, software, platform or network that facilitates the uptake of industrial symbiosis by different economic actors (Maqbool, Mendez Alva, et al., 2019). The project EPOS was also one of these research projects. An assessment of the Information Technology (IT) tools for industrial symbiosis was carried out following the five-stage methodology of Grant et al. (2010). These five stages of industrial symbiosis are; identification, assessment, barrier removal, implementation, and follow up.

Content analysis of publicly available information on 20 symbiosis supporting IT tools revealed a strong focus on synergy identification phase of the symbiosis; while the IT tools lack in supporting the implementation stage of industrial symbiosis. The study indicated newer IT tools now include non-technical information for identifying industrial symbiosis. It is found that successfully operational IT tools are either part of a national or local industrial symbiosis program or owned by a private company. The study recommended that better mechanisms are needed to ensure that publicly funded IT tools for symbiosis successfully reach the market. It was also observed that newer tools tend to focus on the incorporation of tacit knowledge when identifying industrial symbiosis but at this stage it is too early to conclude their efficacy in realising industrial symbiosis.

7.3 INDUSTRIAL FLEXIBILITY AND LOW-CARBON FUTURE

This section responds to the third sub-question which focuses on the effect of industrial electrical flexibility on the transition to a low-carbon electricity grid.

Based on the insights gained from the agent-based model, industries are an enabler to a low-carbon energy system but not noted as the main driver. The model showed that for the industries, 25% of maximum flexibility is observed to be the optimum, at which point the losses made by lost production are balanced by the profit made on the imbalance market. The effect of industrial flexibility is indeed a helpful support mechanism in the bigger frame but a 100% flexibility by industries is not significantly better than a flexible demand at 25%, in terms of profits and curtailing grid imbalances. This is especially relevant when the installed capacity of wind power is above 50% of the system demand. Also, the consumption of renewable energy is not significantly improved by increasing the flexible demand as compared to increasing the installed capacity of renewable energy, pointing to the need for expanding the generation capacity of renewable energy.

For businesses, the decision to provide flexibility as a reserve is complex and can result in major organisational and operational changes. In the model, the industries responded to supply changes regardless of the time of the day and neither did they consider any lead times; in reality, though, this is probably not the case. Although the simulations provide insightful results regarding industries' electrical flexibility as reserves, these results are not extended to other issues. For example, there are legal issues involved when industries plan to market negative tertiary reserve energy in small amounts because of tight storage restrictions (Zwaenepoel et al., 2014). Another reason to keep the industries from providing flexibility as demand response could lie in the relatively low energy price that they pay (as compared to other costs) and could be mitigated by policies opposite to the ones in practice that subsidize heavy-industries (Verzijlbergh et al., 2017). Other incentives for energy intensive industries to reduce their energy costs lie in their ability to install combined heat and power plants. The authors in (Kikuchi et al., 2016) assessed in detail the benefits for industries to engage in symbiotic relations and utilize waste (biomass) to fuel combined heat and power plants. One can argue in favour of symbiosis involving combined heat and power generation and against consumption flexibility, especially if it does not imply disruption in the core production process.

Conclusively, increasing values of installed capacity of wind energy, feed-in tariffs, and industrial flexibility increase the consumption of renewable energy and decreases the market prices; with the effect of installed capacity of wind energy being more significant than the effect of the other two factors. However, the effect of increasing values of consumption flexibility on the profit of producers with storage is not positive, pointing to the need for customized rules and incentives to encourage their market participation and investment in storage facilities. The results support that, in the future, with more renewable energy producers, different market rules may apply to the flexible renewable energy and conventional generation (Peter D. Lund et al., 2015).

Observation of the effect of the industrial flexibility as reserves on the imbalance market helped to observe the self-organisation of the actors. It showed that if the feed-in tariffs are slowly phased out while industrial flexibility increases in parallel, the number of producers with storage will decline but this will not cause extreme imbalance market prices, as the supply fluctuations will be balanced by the flexible industries. However, this effect again points to the need to incentivise the renewable energy producers to invest in storage.

The results support that the renewable energy producers do not have enough incentive to operate more efficiently when feed-in tariffs are being provided to them. There needs to be other support mechanisms that promote investment in storage facilities for the renewable energy producers. Market mechanisms that dictate fines for deviating from nominated power can further demotivate actors in the power generation business to switch to renewable energy technologies. Market mechanisms need to evolve to let more renewable energy producers participate. Additionally, demand side response will aid this transition. As more local balancing agents (aggregators) enter the power networks and virtual power plants are becoming a reality, smart metering would replace net metering systems. This will provide an opportunity to the consumers of all sizes to be flexible in response to production and market signals, ultimately resulting in a truly flexible grid. Depending on the specific markets and their respective mechanisms in different countries, it is up to the policy makers to incentivize the consumers to change, hence create a market pull for producers, and/or incentivize the producers to create a market push for change in the consumer behaviour.

7.4 CONCLUSION

Looking back at the Agenda 21, Chapter 28, the idea of sustainable development is embedded in a concerted bottom-up approach through the participation of the society (United Nations, 1992). Wallner (1999) postulated that society, through self-organisation, becomes a responsible unit able to make decisions that will, in the end, automatically adjust to the criteria of sustainable development. However, the recent climatic changes and conflicts over natural resources have shown a need for long-term vision and governmental support to transition to a sustainable future. One finds one's self in a paradox when theorising societal actions as complex, hence, cannot be controlled, however they should be orchestrated through policy towards sustainability. This thesis dealt with a very small piece of this puzzle.

First, it considered the bottom-up initiatives by industries to engage in industrial symbiosis. Second, it studied the effect of top-down incentives to integrate renewable energy in an electricity grid through feed-in tariffs and imbalance market mechanisms. This helped to answer the main research question of the thesis:

How can the cross-boundary industrial interactions help the move towards resource-efficient and low-carbon future?

The potential of large process industries for the improvement in energy and resource-efficiency through industrial symbiosis helped to answer the former part of the question, related to resource-efficiency. Each of the 28 symbiosis opportunities that were identified and proposed to the industries focused on valuation of the otherwise discarded materials. This proves that there is untapped potential in the process industries to contribute to circular and sustainable economy. The two symbiosis that focused on the interaction between industries and municipalities provided practical insights into the preconditions that lead to successful symbiosis. No matter which identification method for symbiosis is chosen, it is observed that it has to comprise of collecting technical, as well as, non-technical information regarding the potential partners. For this thesis, the LESTS survey and the methodology proved sound to fulfil the purpose of industrial symbiosis identification.

The latter part of the research question focuses on the low-carbon future. Although many of the symbiotic linkages between the industries can help reduce the reliance of industry on fossil fuels, the existing electricity infrastructure was chosen to study how the industries can support renewable energy integration in the grid. The agent-based model included in the thesis showed that without compromising the profits lost through interrupted production, the industries can provide demand side response to balance the grid and also help in reducing the imbalance market prices. Concluding the strategies for top-down incentives for the move to a low-carbon grid, it is proposed that the phase out of the feed-in tariffs should be accompanied by a strategy for increasing the demand side response by industries. Although this may not reduce the high storage costs for the wind farm owners, it will push the system to self-organise and reach an optimum where the industries will provide maximum of 25% flexibility as reserves and the producers of wind energy will opt for no storage facilities. This scenario still requires market mechanisms to protect the producers of renewable energy from the fines incurred due to imbalances in their portfolio.

Thus, this thesis concludes that the bottom-up self-organised symbiotic linkages between industries (and public sector) will need to be met by the top-down incentives to facilitate the move to a resource-efficient and low-carbon future.

ANNEX

Table A-1: The LESTS survey

Questions		Yes	No	Comments / remarks
0. Identification of the Industrial Site				
1	What is the name of the business?			
2	Where is the business located?			
3	What are the main products of your company?			
A. General Information				
	A.1 partner information			
1	Does your company comply by any international or national quality standards?	◉ Yes	○ No	
2	If yes then what kind of reports are these? Environmental surveys, energy surveys, CSR, GRI, etc.			
3	Is there a selection of non-financial key performance indicators (KPIs) of the company?	○ Yes	◉ No	
4	If yes, what are they?			
5	Please explain the foundation of your industrial site: date, reason, development, companies' ownership structure			
	A.2 Cluster site information			
1	What is the area of the industrial cluster? (the whole cluster site)			
2	How many businesses are there in the cluster? (sizing of the cluster will prove helpful in our SWOT analysis)			
3	Is there a strategy for your industrial cluster?	○ Yes	◉ No	
4	If yes, What is the focus of the cluster strategy?			
5	Are you aware of any evaluation criteria if new investors can enter your cluster site? (if other partners can set-up a plant close to your site)	◉ Yes	○ No	
6	If yes, please explain this criteria			
	A.3 Cluster Management			
1	Is there a management plan for your industrial cluster?	○ Yes	◉ No	

2	Is there a central management body/person active at the cluster site?	○ Yes ◉ No
3	If yes, What are the responsibilities of cluster manager or management	
	A.4 Consultation at Cluster level	
1	Does any inter-company co-operation take place in the cluster?	○ Yes ◉ No
	Especially with any industry partner?	
2	Do the companies consult each other periodically?	◉ Yes ○ No
3	Is there an obligation by public law for inter-business cooperation in your region?	○ Yes ◉ No
4	Is there a platform that provides subscription / initiation for new companies to participate in cluster activities?	◉ Yes ○ No
B. Environmental Factors		
	B.1 Materials (Technical industrial symbiosis)	
1	Do you have an environmental management system in place for your cluster? (will make it easier to pinpoint material flows, discrepancies in the system, etc.)	◉ Yes ○ No
2	If yes, Who is responsible for the environmental monitoring of the environmental performance of the cluster?	
3	What monitoring systems of the environment are established? land emissions water waste other	
	B1.1 By-products and waste	
1	What are your biggest co-product streams?	
2	How are they handled now? (emitted to environment, treated, landfilled, etc.)	
3	What do you intend to achieve from these co-products?	

4	What amount of these streams are produced by your company annually? (each waste stream, each co-product or by-product stream)	
5	What are your biggest waste streams?	
6	How do you treat the waste?	
7	Will you be interested in valorising the waste streams?	
8	Is there any mechanism for combined waste treatment at your cluster?	○ Yes ◉ No
	If yes, please answer following questions	
9	Who is responsible for the waste treatment?	
10	What is the payment system?	
11	Can the waste management contract be extended to new companies?	
12	Why did you choose this waste treatment method / company ..	

	B1.2 Emissions	
1	Which emission streams (CO_2, SO_x, NO_x) are monitored by your industry (to be used for proposing industrial symbiosis proposals)?	
2	Is there any mechanism for combined effluent air treatment at your site?	○ Yes ◉ No
	If yes, please answer following questions	
3	Who is responsible for the effluent air treatment?	
4	What is the payment system?	
5	Can the effluent air management contract be extended to new companies?	○ Yes ◉ No
6	Why did you choose this effluent air treatment method / company ..	
7	What is your company interest with regards to air emissions?	
8	Please indicate if you intend to engage in a collaboration on site for emissions reduction	◉ Yes ○ No

	B1.3 Energy	
1	Is there an on-site energy production for your industrial site (renewable energy production or utilization)?	○ Yes ◉ No
2	If yes, What is the share of renewable energy utilised by your industry?	

3	Do you have a waste heat recovery unit on site	○ Yes ◉ No
	If yes,	
4	What is the project?	
5	Do you share it with any other companies?	○ Yes ◉ No
6	What is the financial benefit?	
7	Can the project contract be extended to new companies?	
8	Why did you choose this energy cogeneration method / project ..	
9	Is there any mechanism for energy cogeneration?	○ Yes ◉ No
	If yes,	
10	What is the project?	
11	Do you share it with any other companies?	○ Yes ◉ No
12	What are the financial benefits?	
13	Can the project contract be extended to new companies?	
14	Why did you choose this energy cogeneration method / project ..	
15	Are there any public incentives for energy use reduction? (subsidies, tax reductions, etc)	◉ Ye ○ No
16	If yes, please indicate which incentives are there?	
17	If any, what do you intend to do with your energy waste streams?	

	B1.4 Water	
1	What is the source of your water? (groundwater, rain, recycled water, freshwater, other?)	
2	How much water is discharged into the environment from your company annually?	
3	What are the biggest pollution parameters for the effluent water?	
4	Do companies know each other's effluent composition?	○ Yes ◉ No
5	Is it a legislative need?	○ Yes ◉ No

6	Is there any mechanism for combined wastewater treatment?	○ Yes ◉ No
	If yes,	
7	What is the project?	
8	Do you share it with any other companies?	◉ Yes ○ No
9	What are the financial benefits?	
10	Can the project contract be extended to new companies?	
11	Why did you choose this water treatment method / service ..	
12	Please indicate if your company will be interested in reducing the water use on site?	◉ Yes ○ No
13	If so, how do you intend to do it?	
14	Are third parties on your cluster site interested in collaborating to reduce water use?	○ Yes ◉ No
	If yes,	
15	Which companies are these?	
16	What is the economic interest?	
17	What is the environmental benefit?	
18	What type of contract will it be?	
	B.2 Processes and Services	
	B2.1 Supply Chain	
1	Is there an appointed person in your company in charge of checking for sustainability of your supply chain?	○ Yes ◉ No
2	Is the following information available?	
3	a sketch of all the supply chain actors	○ Yes ◉ No
4	a written declaration of all supply chain actors showing their commitment to CSR (Corporate Social Responsibility) criteria	○ Yes ◉ No
5	Does your company take into account of the ethical origin of products?	○ Yes ◉ No
6	Is there any collaboration with other companies on your cluster site with shared	
7	Procurement	○ Yes ◉ No
8	If yes, please explain the collaboration	

9	Storage	◉ Yes ○ No
10	If yes, please explain the collaboration	
11	Transport	○ Yes ◉ No
12	If yes, please explain the collaboration	
13	Other	
14	If yes, please explain the collaboration	
15	If these facilities are not shared already, will you be interested in sharing them with neighbouring businesses?	◉ Yes ○ No
16	What kind of supply chain collaboration can you offer to your neighbouring industries?	
17	What kind of supply chain collaboration will you be interested in from your neighbouring industries?	
	B2.2 Packaging	
1	What are your packaging requirements?	
2	Is there any shared purchase of packaging?	○ Yes ◉ No
3	If yes, please explain the collaboration	
4	If no, Will you be interested in joint purchase of packaging?	○ Yes ◉ No
5	Which facilities do you use for packaging that can be shared	
6	Do you recycle your packaging material?	◉ Yes ○ No
8	If yes, please explain the activity	
9	What are the financial benefits in recycling your packaging material	
10	Can you expand the activity to neighbouring industry?	○ Yes ◉ No
	B2.3 Equipment	
1	Are there any large equipment that you will be interested in to share with other companies?	○ Ye ◉ No
2	If yes, what kind of equipment is it?	
	B2.4 employee facilities	
1	Are the restaurants shared with other companies on site?	○ Yes ◉ No

2	Are there any physical and mental health facilities for your employees? (possibility to extend the service to other businesses in neighbourhood)		
	B2.5 Mobility		
1	What is the current mode of transport of employees to your cluster site		
2	Is there a collective mobility plan for the employees on site?		
3	Do you share that facility with other companies?	Yes	No (selected)
4	Are other companies interested in combined mobility plan?	Yes	No (selected)
	B.3 Multiple factors for non-technical industrial symbiosis		
1	What is the state of the combined grounds (empty plots) on the site?		
2	Do you have any free land for setting up a new plant?	Yes (selected)	No
3	Are the communal parts of the cluster collectively maintained?	Yes	No (selected)
4	If yes, how does this happen?		
5	Which, if any, private property or facilities can be collectively maintained? (private green, building, technical equipment, etc.)		
6	Is there a knowledge platform which can lead to filling vacancies, staff exchanges? (Seasonal workers, maintenance workers, janitors, etc.) for example - an employee works for two companies on the site under the same contract	Ye	No (selected)
7	If yes, how does this happen?		
8	Are the employees trained collectively by companies? for example - within a cluster employees can have same skills and the combined trainings may prove more efficient	Yes	No (selected)
	C. Organisational and Motivational Factors		
	C.1 Stakeholder analysis		

1	Are you aware of any businesses in your vicinity who are interested in a possible collaboration that will result in an industrial symbiosis?	◉ Yes ○ No
2	If yes, please explain the collaboration	
3	Please identify the businesses of your interest at your cluster site for possible industrial symbiosis	
4	What are your interests in starting a collaboration with third parties in your cluster site	
	C.2 Decision making power	
1	Do you make business decisions independent of the central headquarters?	◉ Yes ○ No
2	Can you indicate the level of independence in business that you can practice (scale 0 to 5)	
	C.3 Stakeholder engagement	
1	Among the neighbouring business, identify the ones with whom your business already has contracts	
2	What kind of contracts do you have with these businesses?	
3	Are there informal contacts or communication platforms that promote collaboration between business on the site?	◉ Yes ○ No
4	Are you interested in such initiatives?	
5	Are you aware if other business are interested in these initiatives also?	
D. Informational Factors		
	D.1 Resistance to disclose information	
1	Is there consultation with the education sector?	◉ Ye ○ No
2	Is there consultation with NGOs?	○ Ye ◉ No
3	Is there consultation with consumers?	◉ Ye ○ No
4	other stakeholders?	
5	Which currently unavailable consultation would you consider still appropriate for your company?	
	D.2 Information Management Systems	
1	Is there any information management system for the cluster site?	◉ Ye ○ No

	If so,	
2	Who operates it?	
3	Which information does it provide?	
4	Is it made for technical staff or the managerial staff?	
	If no,	
5	How does information between different companies on the cluster take place?	
6	Will you be interested in such an information management system?	○ Yes ◉ No
7	What will your company be interested in adding in such an information management system?	
8	Are there any knowledge platforms present for different companies to use?	○ Yes ◉ No
9	If yes, what kind of platforms are these?	
10	Have you considered closing the loop on your products? (tracing the end products back to your industry for re-use or recycling)	○ Yes ◉ No
11	Did your company couple a service to a physical products with the past few years? (more a Circular Economy question)	○ Yes ◉ No
	Other?	
	If anything has been missed in the survey please mention	
	Potential opportunities	
	Feedback on the survey	

Table A-2: Preliminary list of opportunities for collaboration in Rudniki cluster

	Possibilities to collaborate	Explanation
Waste	Use of by-product from one industry in another (Cement – Minerals – Steel);	Slag from Steel can be used as raw material in Cement plant.
		Reject stream ($CaCO_3$) from Minerals can be used as raw material in Cement plant or by Engineering company for waste treatment.
		Steel slag for Steel can be utilised for neutralisation in wastewater treatment plant (WWTP). Also for extraction of metals form wastewater treatment.
Emissions	Collaboration in carbon capture and storage (all partners);	All partners indicate CO_2 emissions as a concern. A joined effort to finance carbon capture and storage could be of interest for all partners.
Energy	Planning and applying for funding for renewable energy projects (all partners);	All industries have shown interest in renewable energy projects. A shared effort to apply for subsidies and incentives for renewable energy projects can prove useful for all partners in Rudniki cluster.
Non-process based activities	Shared logistics, equipment and procurement.	Health and Safety trainings can be collectively arranged for employees of partners

Table A-3: Other opportunities for resource and energy efficiency for the Rudniki cluster

Opportunity	Status
Electricity production at Cement with the help of ORC or Kalina Cycle at Cement	
Electricity production by installing an ORC/ Kalina cycle using the cooling unit exhaust gas and milling unit exhaust gas. Since Cement plant will undergo a number of changes in near future, it could be an interesting option for Cement after the modernisation of the infrastructure.	For now this is not a very attractive opportunity for Cement
Virtual power plant at Cement	
Cement is part of a virtual power plant (VPP), called Espirion. Espirion is a national initiative by the Polish government. If requested by the VPP, Cement has accepted to switch off some units that are connected to the VPP, during the day time. During the night, Cement can keep its production processes running without any hindrance. Cement gets a fee from Espirion for being a part of the VPP and Cement also has the right to ask for a further fee, when asked to shut down the selected units. Other companies can also connect to the VPP, by learning from the experience of Cement. The VPP provides 6-12 MW of flexibility in electricity.	Cement is at 'ready to go' stage
CHP in Krakow with Steel	
Steel can replicate the DHN in Krakow region. The supply of steel mill off-gases can be used as alternative fuel. Depending on the willingness of Steel, this synergy can be further explored with the help of the industrial symbiosis facilitation toolbox. While considering the LESTS aspects of the synergy, such a DHN can help Steel gain white certificates. White certificates are a good monetary incentive to put in place projects that reduce energy consumption.	No contact with Steel
Sludge from Steel to Cement	
The iron rich sludge from steel industry is mixed with coal ash and used as raw material in cement production.	No contact with Steel
ORC at Minerals	
Minerals can use waste heat to produce electricity for their own use. The estimates provided by Korona are as follows: •Capacity 65-5000 kW, CAPEX 1500-4500€/kW , OPEX 0.55-14€/h	Little to no interest from Minerals

Table A-4: Preliminary list of opportunities for collaboration in Lavéra cluster

Possibilities to collaborate	Explanation

Waste	Use of by-product from one industry as fuel in another (Chemical-AM)	Steel slag for Steel can be utilised for neutralisation in WWTP of Chemical Lavéra. Also for extraction of metals form wastewater treatment.
Emissions	Collaboration in carbon capture and storage (all partners)	All industry partners indicate CO2 emissions as a concern. A joined effort to finance carbon capture and storage could be of interest for all partners.
Water	Replace freshwater use by treated water (Chemical – potential industry partner)	Chemical Lavéra wishes to reduce their use of freshwater and are willing to look for possible substitution projects.
	Shared WWTP (Steel and Chemical)	WWTP at Chemical Lavéra site is oversized (24 t/d TOD). Effluents from the chemical park approximately represent 8 t/d of TOD. The WWTP can thus treat third parties effluents.
Energy	District heating / cooling network (Chemical and AM)	Both industries have shown interest in connecting to a district heating network.
Non-process based activities	Combined employee training for health and safety	Health and safety trainings can be collectively arranged for employees of industry partners.
Combined management	Shared gas balancing (Chemical-AM)	Chemical can extend their service of gas balancing to Steel Fos.

Table A-5: Other opportunities for resource and energy efficiency for the industry Lavera cluster

Opportunity	Status
1. COG, BFG and BOFG from Steel to Chemical	
Recovery of valuable gas components (H_2 fraction extraction: about 60% of COG, almost nothing from the others). Chemical can refine the gases on their site and use H_2 as raw material. Or Steel refines the gases on their site and transport H_2 or CH_4 to Chemical. Depending on the mode of transport chosen and end-use, the storage facilities will need to be allocated to either of the parties. A combined investment could be made in the project	Due to difficulty to build a connection between the two sites, the industrial symbiosis is not a priority for the companies
Since methanol is easier to transport, the COG can be converted to methanol and sold on the market. Either Steel can valorise the flow for selling it to third party or sell it to Chemical for use.	Due to difficulty to build a connection between the two sites, the industrial symbiosis is not a priority for the companies
2. Electricity production from hydrogen and other process gases at Steel	
Since there is a high concentration of Hydrogen in COG, this can be separated and used in either hydrogen vehicles or converted to electricity to run electric vehicles. Chemical already has a fleet of electric vehicles for use by the employees in Lavera cluster. There could be a knowledge synergy between the two companies.	The number of Steel employees is too small and not economically viable to invest in such an initiative.
3. Upgradation of low pressure steam at Chemical	
The excess steam at Chemical can be valorised by raising the temp and pressure of low pressure steam for use in other processes (mechanical vapour recompression - MVR). Since Steel has not shown interest in sharing this stream, Chemical can look for an external partner. Since, it is beyond the scope of industry, the synergy is not further explored.	Proposal
4. Wastewater from Steel and Chemical	
Sending wastewater from Steel to Chemical Lavera site. There is an overcapacity at the wastewater treatment plant in Lavera, which could be used by Steel. However, the WWTP is handled by a third party on Lavera site, hence, making it more difficult to carry out a full analysis of the feasibility. Also, the incoming wastewater's quality has to fulfil certain	Proposal

criteria, which are necessary for the successful running of the biological processes in the WWTP.

Table A-6: Preliminary list of opportunities for partners in Humber cluster

	Possibilities to collaborate	Explanation
Waste	Use of by-product from one industry as fuel in another (Chemical-Cement)	Chemical Hull produces a liquid waste stream with high calorific value and Cement has a permit to burn 100% waste derived fuel in the kiln, they still have 20% of capacity that they can replace with waste.
	Valorisation of waste stream (Chemical-potential partner)	Chemical can install specific membrane filtration to separate hydrocarbon component present in some purge streams (higher value stream) for recycling in the system or use outside the plant boundary.
	Combined waste management contract (Engineering company – Minerals, Cement and Chemical)	Engineering company is very active in the Humber cluster and already has contracts with Cement and Chemical. It will be of interest to see if these collaborations can be extended to include all three partners.
	Exchange of by-products between two industries (Cement and Minerals)	A by-product stream rich in calcium carbonate from Minerals can be sent to Cement to be used as raw material and CKD from Cement can be sent back to Minerals for landscaping. Cement Kiln Dust (alkaline in nature) from Cement is already used for soil reclamation of acidic soils; there could be other possibilities for CKD, e.g. use by the Engineering company for waste treatment.
Emissions	Collaboration in carbon capture and storage (all partners)	All three industry partners indicate CO_2 emissions as a concern. A joined effort to finance carbon capture and storage could be of interest for all partners.
	CO_2 from industry to local businesses (Minerals and Cement)	Cement has tomato growers in their plant's vicinity and they can transport captured carbon to tomato growers. This synergy can also be extended to other industry partners.

		A dry ice producer can be invited to set-up a plant close to Minerals or Cement. Both partners own empty plots and can lease them to other companies.
Water	Replace freshwater use by treated water (Cement – potential industry partner)	Cement wishes to reduce their use of freshwater from Humber river. Although the use of river water also plays a role in flood control during summer season.
Energy	District heating network (Cement and South Ferriby region)	Cement has shown interest in engaging in a district heating network using their low heat streams of 120 °C and 200 °C.
	Replace use of non-renewable energy with renewable energy (Minerals – all industry partners)	There is a strong interest of all industry partners to increase their use of renewable energy. Minerals, in collaboration with a third party, has an ongoing project of installing wind turbines. industry partners can benefit from this opportunity by shared use of green electricity. All industry partners have an opportunity to install a small micro-hydro turbine on the river Humber and reduce their use of non-renewable energy.
Non-process based activities	Combined employee training for health and safety (Engineering company- all industry partners)	The Engineering company holds trainings for The Engineering company employees and the special trainings for Health and Safety practices can also be arranged for employees of industry partners.
	Shared reporting service (all industry partners)	ESOS, EED, waste management reports, etc., could be outsourced or carried out by specialists on site collectively for the industry partners.
	Joint negotiation and marketing for renewable energy projects (all industry partners)	Feedback from Cement shows that wind turbines are opposed by local community, the three industry partners join efforts in negotiating with community and invest collectively for setting up the wind turbines by marketing the projects and their benefits for local and global community.
	Combined efforts in RnD on forthcoming stricter dust emission regulations (Minerals and Cement)	Legislation on permissible PM size for release in atmosphere is foreseen to be stricter in future. Very expensive scrubbers are needed to be installed by Cement and Minerals to abide by these laws. Either the industry can invest in

		combined purchase of equipment or join in RnD activities to tackle this problem.
	Shared subscription of employees at the local health and fitness facilities	Since the distance between the three partners does not allow for sharing employee facilities like shared cafeteria, health and fitness services, etc., the possibility to increase informal communication between their employees via joining same facilities is one way to strengthen the trust between the industry company employees.
Combined site management	Combined land maintenance	All these activities are necessary on the plants and can be carried out collectively. Lawn maintenance, gardening services, seasonal cleaning service, window cleaning, etc.
	Combined shuttle service for employees	
	Common accommodation for visitors	
	Combined insurance for employees	

Table A-7: Other opportunities for resource and energy efficiency for the Humber cluster

Opportunity	Status
1. CO_2 and waste heat to the local green houses	
The CO_2 produced at Minerals and Cement's plant can be purified and along with the excess heat could be sent to the neighbouring green houses. No techno-economic analysis has been carried out so far.	Little or no interest at the moment
2. Onsite energy optimisation / production	
Installation of ORC/Kalina cycle at Cement to produce electricity A micro-hydro turbine can be installed to produce electricity for Cement, since Cement South Ferriby is right next to the river. There is still a need to carry out an analysis of costs and certifications involved.	Little to no interest
Minerals and a third party had been in the process of installing Wind turbines in the vicinity. The synergy had been studied for different benefits for the companies in the Hull region, however, the synergy is difficult to be shared or replicated for other companies. It is difficult for the other companies to connect to the wind turbines through a direct cable, since it will require heavy investment, time and lengthy legal procedures to get a permit for installation of a cable through private land. If the companies share the clean energy via the grid, then there are no financial gains left for any of the partners. Since, Minerals will have to pay for using the grid and the other companies will also need to pay a fee to use the grid. Also, there is no legal mechanism in place in UK that ensures that the existing network of cables could be used for connecting to clean energy producers and benefits or ETS credits could be claimed by the clean energy users.	Final economic assessment shows that there is marginal benefit and Minerals management have not yet committed to the project
Upgradation of Minerals waste heat streams for the purpose of cooling or heating could be achieved by the installation of absorption/adsorption heat pumps to upgrade heat stream, or alternatively by use of absorption chillers to generate cold (-60 °C to 10 °C)	Little to no interest

Figure A1: Annualised day ahead market prices for different values of ω and τ under the effect of increasing Δ_x

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